(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
6 May 2004 (06.05.2004)

PCT

(10) International Publication Number
WO 2004/039022 A2

(51) International Patent Classification[7]: H04L 25/02, 5/14

(21) International Application Number:
PCT/US2003/034515

(22) International Filing Date: 24 October 2003 (24.10.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/421,462	25 October 2002 (25.10.2002)	US
60/421,309	25 October 2002 (25.10.2002)	US
10,693,169	23 October 2003 (23.10.2003)	US

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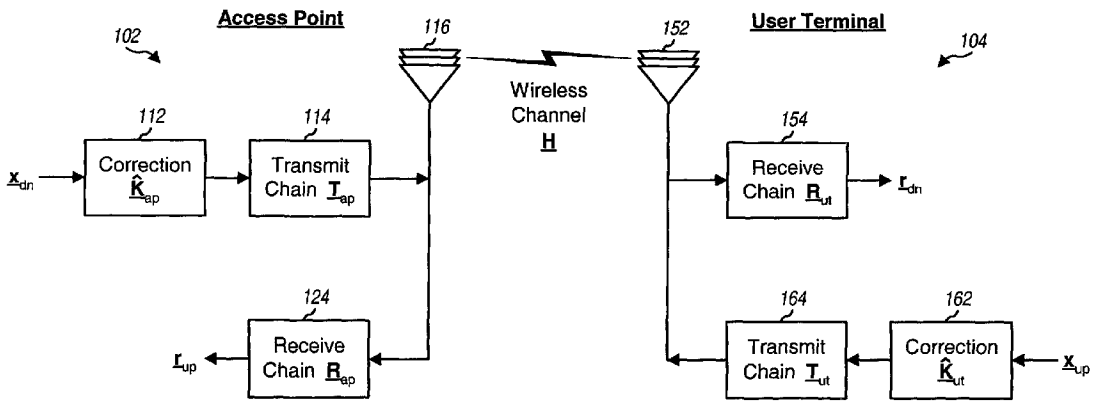
(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CHANNEL CALIBRATION FOR A TIME DIVISION DUPLEXED COMMUNICATION SYSTEM



(57) Abstract: Techniques to calibrate the downlink and uplink channels to account for differences in the frequency responses of the transmit and receive chains at an access point and a user terminal. In one embodiment, pilots are transmitted on the downlink and uplink channels and used to derive estimates of the downlink and uplink channel responses, respectively. Two sets of correction factors are then determined based on the estimates of the downlink and uplink channel responses. A calibrated downlink channel is formed by using a first set of correction factors for the downlink channel, and a calibrated uplink channel is formed by using a second set of correction factors for the uplink channel. The first and second sets of correction factors may be determined using a matrix-ratio computation or a minimum mean square error (MMSE) computation. The calibration may be performed in real-time based on over-the-air transmission.

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CHANNEL CALIBRATION FOR A TIME DIVISION DUPLEXED COMMUNICATION SYSTEM

Claim of Priority under 35 U.S.C. §119

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 60/421,462, entitled, "Channel Calibration for a Time Division Duplexed Communication System," and U.S. Provisional Application Serial No. 60/421,309, entitled, "MIMO WLAN System," both of which are filed on October 25, 2002, assigned to the assignee of the present application, and incorporated herein by reference.

BACKGROUND

Field

[0002] The present invention relates generally to communication, and more specifically to techniques for calibrating downlink and uplink channel responses in a time division duplexed (TDD) communication system.

Background

[0003] In a wireless communication system, data transmission between an access point and a user terminal occurs over a wireless channel. Depending on the system design, the same or different frequency bands may be used for the downlink and uplink. The downlink (or forward link) refers to transmission from the access point to the user terminal, and the uplink (or reverse link) refers to transmission from the user terminal to the access point. If two frequency bands are available, then the downlink and uplink may be transmitted on separate frequency bands using frequency division duplexing (FDD). If only one frequency band is available, then the downlink and uplink may share the same frequency band using time division duplexing (TDD).

[0004] To achieve high performance, it is often necessary to know the frequency response of the wireless channel. For example, the response of the downlink channel may be needed by the access point to perform spatial processing (described below) for downlink data transmission to the user terminal. The downlink channel response may be estimated by the user terminal based on a pilot transmitted by the access point. The user terminal may then send the channel estimate back to the access point for its use. For this channel estimation scheme, a pilot needs to be transmitted on the downlink and

additional delays and resources are incurred to send the channel estimate back to the access point.

[0005] For a TDD system with a shared frequency band, the downlink and uplink channel responses may be assumed to be reciprocal of one another. That is, if $\underline{\mathbf{H}}$ represents a channel response matrix from antenna array A to antenna array B, then a reciprocal channel implies that the coupling from array B to array A is given by $\underline{\mathbf{H}}^T$, where $\underline{\mathbf{M}}^T$ denotes the transpose of matrix $\underline{\mathbf{M}}$. Thus, for a TDD system, the channel response for one link may be estimated based on a pilot sent on the other link. For example, the uplink channel response may be estimated based on an uplink pilot, and the transpose of the uplink channel response estimate may be used as an estimate of the downlink channel response.

[0006] However, the frequency responses of the transmit and receive chains at the access point are typically different from the frequency responses of the transmit and receive chains at the user terminal. In particular, the frequency responses of the transmit/receive chains used for uplink transmission may be different from the frequency responses of the transmit/receive chains used for downlink transmission. The "effective" downlink channel response (i.e., including the transmit/receive chains) would then be different from the reciprocal of the effective uplink channel response due to differences in the transmit/receive chains (i.e., the effective channel responses are not reciprocal). If the reciprocal of the channel response estimate obtained for one link is used for spatial processing on the other link, then any difference in the frequency responses of the transmit/receive chains would represent error that, if not determined and accounted for, may degrade performance.

[0007] There is, therefore, a need in the art for techniques to calibrate the downlink and uplink channels in a TDD communication system.

SUMMARY

[0008] Techniques are provided herein to calibrate the downlink and uplink channels to account for differences in the frequency responses of the transmit and receive chains at the access point and user terminal. After calibration, an estimate of the channel response obtained for one link may be used to obtain an estimate of the channel

response for the other link. This can then simplify the channel estimation and spatial processing.

[0009] In one embodiment, a method is provided for calibrating the downlink and uplink channels in a wireless TDD multiple-input multiple-output (MIMO) communication system. In accordance with the method, a pilot is transmitted on the uplink channel and used to derive an estimate of the uplink channel response. A pilot is also transmitted on the downlink channel and used to derive an estimate of the downlink channel response. Two sets of correction factors are then determined based on the estimates of the downlink and uplink channel responses. A calibrated downlink channel is formed by using a first set of correction factors for the downlink channel, and a calibrated uplink channel is formed by using a second set of correction factors for the uplink channel. The appropriate correction factors will be used at the respective transmitter for the downlink and uplink channels. The responses of the calibrated downlink and uplink channels are approximately reciprocal due to the two sets of correction factors. The first and second sets of correction factors may be determined using a matrix-ratio computation or a minimum mean square error (MMSE) computation, as described below.

[0010] The calibration may be performed in real-time based on over-the-air transmission. Each user terminal in the system may derive the second set of correction factors for its own use. The first set of correction factors for the access point may be derived by multiple user terminals. For an orthogonal frequency division multiplexing (OFDM) system, the calibration may be performed for a first set of subbands to obtain two sets of correction factors for each subband in the set. Correction factors for other "uncalibrated" subbands may be interpolated based on the correction factors obtained for the "calibrated" subbands.

[0011] Various aspects and embodiments of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[0013] FIG. 1 shows the transmit and receive chains at an access point and a user terminal in a MIMO system;

[0014] FIG. 2 illustrates the application of correction factors to account for differences in the transmit/receive chains at the access point and user terminal;

[0015] FIG. 3 shows a process for calibrating the downlink and uplink channel responses in a TDD MIMO-OFDM system;

[0016] FIG. 4 shows a process for deriving estimates of the correction vectors from the downlink and uplink channel response estimates;

[0017] FIG. 5 is a block diagram of the access point and user terminal; and

[0018] FIG. 6 is a block diagram of a TX spatial processor.

DETAILED DESCRIPTION

[0019] The calibration techniques described herein may be used for various wireless communication systems. Moreover, these techniques may be used for single-input single-output (SISO) systems, multiple-input single-output (MISO) systems, single-input multiple-output (SIMO) systems, and multiple-input multiple-output (MIMO) systems.

[0020] A MIMO system employs multiple (N_T) transmit antennas and multiple (N_R) receive antennas for data transmission. A MIMO channel formed by the N_T transmit and N_R receive antennas may be decomposed into N_S independent channels, with $N_S \leq \min\{N_T, N_R\}$. Each of the N_S independent channels is also referred to as a spatial subchannel or an eigenmode of the MIMO channel and corresponds to a dimension. The MIMO system can provide improved performance (e.g., increased transmission capacity) if the additional dimensionalities created by the multiple transmit and receive antennas are utilized. This typically requires an accurate estimate of the channel response between the transmitter and receiver.

[0021] **FIG. 1** shows a block diagram of the transmit and receive chains at an access point 102 and a user terminal 104 in a MIMO system. For this system, the downlink and uplink share the same frequency band in a time division duplexed manner.

[0022] For the downlink, at access point 102, symbols (denoted by a "transmit" vector $\underline{\mathbf{x}}_{dn}$) are processed by a transmit chain (TMTR) 114 and transmitted from N_{ap} antennas 116 over a wireless channel. At user terminal 104, the downlink signals are received by

N_{ut} antennas 152 and processed by a receive chain (RCVR) 154 to provide received symbols (denoted by a "receive" vector $\underline{\mathbf{r}}_{\text{dn}}$). The processing by transmit chain 114 typically includes digital-to-analog conversion, amplification, filtering, frequency upconversion, and so on. The processing by receive chain 154 typically includes frequency downconversion, amplification, filtering, analog-to-digital conversion, and so on.

[0023] For the uplink, at user terminal 104, symbols (denoted by transmit vector $\underline{\mathbf{x}}_{\text{up}}$) are processed by a transmit chain 164 and transmitted from N_{ut} antennas 152 over the wireless channel. At access point 102, the uplink signals are received by N_{ap} antennas 116 and processed by a receive chain 124 to provide received symbols (denoted by receive vector $\underline{\mathbf{r}}_{\text{up}}$).

[0024] For the downlink, the receive vector at the user terminal may be expressed as:

$$\underline{\mathbf{r}}_{\text{dn}} = \underline{\mathbf{R}}_{\text{ut}} \underline{\mathbf{H}} \underline{\mathbf{T}}_{\text{ap}} \underline{\mathbf{x}}_{\text{dn}} , \qquad \text{Eq (1)}$$

where $\underline{\mathbf{x}}_{\text{dn}}$ is the transmit vector with N_{ap} entries for the symbols transmitted from the N_{ap} antennas at the access point;

$\underline{\mathbf{r}}_{\text{dn}}$ is the receive vector with N_{ut} entries for the symbols received on the N_{ut} antennas at the user terminal;

$\underline{\mathbf{T}}_{\text{ap}}$ is an $N_{ap} \times N_{ap}$ diagonal matrix with entries for the complex gains associated with the transmit chain for the N_{ap} antennas at the access point;

$\underline{\mathbf{R}}_{\text{ut}}$ is an $N_{ut} \times N_{ut}$ diagonal matrix with entries for the complex gains associated with the receive chain for the N_{ut} antennas at the user terminal; and

$\underline{\mathbf{H}}$ is an $N_{ut} \times N_{ap}$ channel response matrix for the downlink.

The responses of the transmit/receive chains and the wireless channel are typically a function of frequency. For simplicity, a flat-fading channel (i.e., with a flat frequency response) is assumed.

[0025] For the uplink, the receive vector at the access point may be expressed as:

$$\underline{\mathbf{r}}_{\text{up}} = \underline{\mathbf{R}}_{\text{ap}} \underline{\mathbf{H}}^{T} \underline{\mathbf{T}}_{\text{ut}} \underline{\mathbf{x}}_{\text{up}} , \qquad \text{Eq (2)}$$

where $\underline{\mathbf{x}}_{up}$ is the transmit vector for the symbols transmitted from the N_{ut} antennas at the user terminal;

$\underline{\mathbf{r}}_{up}$ is the receive vector for the symbols received on the N_{ap} antennas at the access point;

$\underline{\mathbf{T}}_{ut}$ is an $N_{ut} \times N_{ut}$ diagonal matrix with entries for the complex gains associated with the transmit chain for the N_{ut} antennas at the user terminal;

$\underline{\mathbf{R}}_{ap}$ is an $N_{ap} \times N_{ap}$ diagonal matrix with entries for the complex gains associated with the receive chain for the N_{ap} antennas at the access point; and

$\underline{\mathbf{H}}^T$ is an $N_{ap} \times N_{ut}$ channel response matrix for the uplink.

[0026] For a TDD system, since the downlink and uplink share the same frequency band, a high degree of correlation normally exists between the downlink and uplink channel responses. Thus, the downlink and uplink channel response matrices may be assumed to be reciprocal (i.e., transposes) of each other and denoted $\underline{\mathbf{H}}$ and $\underline{\mathbf{H}}^T$, respectively, as shown in equations (1) and (2). However, the responses of the transmit/receive chains at the access point are typically not equal to the responses of the transmit/receive chains at the user terminal. The differences then result in the following inequality $\underline{\mathbf{R}}_{ap}\underline{\mathbf{H}}^T\underline{\mathbf{T}}_{ut} \neq (\underline{\mathbf{R}}_{ut}\underline{\mathbf{H}}\underline{\mathbf{T}}_{ap})^T$.

[0027] From equations (1) and (2), the "effective" downlink and uplink channel responses, $\underline{\mathbf{H}}_{dn}$ and $\underline{\mathbf{H}}_{up}$, which include the responses of the applicable transmit and receive chains, may be expressed as:

$$\underline{\mathbf{H}}_{dn} = \underline{\mathbf{R}}_{ut}\underline{\mathbf{H}}\underline{\mathbf{T}}_{ap} \quad \text{and} \quad \underline{\mathbf{H}}_{up} = \underline{\mathbf{R}}_{ap}\underline{\mathbf{H}}^T\underline{\mathbf{T}}_{ut} \; . \qquad \text{Eq (3)}$$

Combining the two equations in equation set (3), the following relationship may be obtained:

$$\underline{\mathbf{R}}_{ut}^{-1}\underline{\mathbf{H}}_{dn}\underline{\mathbf{T}}_{ap}^{-1} = (\underline{\mathbf{R}}_{ap}^{-1}\underline{\mathbf{H}}_{up}\underline{\mathbf{T}}_{ut}^{-1})^T = \underline{\mathbf{T}}_{ut}^{-1}\underline{\mathbf{H}}_{up}^T\underline{\mathbf{R}}_{ap}^{-1} \; . \qquad \text{Eq (4)}$$

Rearranging equation (4), the following is obtained:

$$\underline{\mathbf{H}}_{up}^T = \underline{\mathbf{T}}_{ut}\underline{\mathbf{R}}_{ut}^{-1}\underline{\mathbf{H}}_{dn}\underline{\mathbf{T}}_{ap}^{-1}\underline{\mathbf{R}}_{ap} = \underline{\mathbf{K}}_{ut}^{-1}\underline{\mathbf{H}}_{dn}\underline{\mathbf{K}}_{ap}$$

or

$$\underline{\mathbf{H}}_{up} = (\underline{\mathbf{K}}_{ut}^{-1}\underline{\mathbf{H}}_{dn}\underline{\mathbf{K}}_{ap})^{T}, \qquad \text{Eq (5)}$$

where $\underline{\mathbf{K}}_{ut} = \underline{\mathbf{T}}_{ut}^{-1}\underline{\mathbf{R}}_{ut}$ and $\underline{\mathbf{K}}_{ap} = \underline{\mathbf{T}}_{ap}^{-1}\underline{\mathbf{R}}_{ap}$. Equation (5) may also be expressed as:

$$\underline{\mathbf{H}}_{up}\underline{\mathbf{K}}_{ut} = (\underline{\mathbf{H}}_{dn}\underline{\mathbf{K}}_{ap})^{T} \quad . \qquad \text{Eq (6)}$$

[0028] The left-hand side of equation (6) represents the calibrated channel response on the uplink, and the right-hand side represents the transpose of the calibrated channel response on the downlink. The application of the diagonal matrices, $\underline{\mathbf{K}}_{ut}$ and $\underline{\mathbf{K}}_{ap}$, to the effective downlink and uplink channel responses, as shown in equation (6), allows the calibrated channel responses for the downlink and uplink to be expressed as transposes of each other. The $(N_{ap} \times N_{ap})$ diagonal matrix $\underline{\mathbf{K}}_{ap}$ for the access point is the ratio of the receive chain response $\underline{\mathbf{R}}_{ap}$ to the transmit chain response $\underline{\mathbf{T}}_{ap}$ (i.e., $\underline{\mathbf{K}}_{ap} = \frac{\underline{\mathbf{R}}_{ap}}{\underline{\mathbf{T}}_{ap}}$), where the ratio is taken element-by-element. Similarly, the $(N_{ut} \times N_{ut})$ diagonal matrix $\underline{\mathbf{K}}_{ut}$ for the user terminal is the ratio of the receive chain response $\underline{\mathbf{R}}_{ut}$ to the transmit chain response $\underline{\mathbf{T}}_{ut}$.

[0029] The matrices $\underline{\mathbf{K}}_{ap}$ and $\underline{\mathbf{K}}_{ut}$ include values that can account for differences in the transmit/receive chains at the access point and user terminal. This would then allow the channel response for one link to be expressed by the channel response for the other link, as shown in equation (6).

[0030] Calibration may be performed to determine the matrices $\underline{\mathbf{K}}_{ap}$ and $\underline{\mathbf{K}}_{ut}$. Typically, the true channel response $\underline{\mathbf{H}}$ and the transmit/receive chain responses are not known nor can they be exactly or easily ascertained. Instead, the effective downlink and uplink channel responses, $\underline{\mathbf{H}}_{dn}$ and $\underline{\mathbf{H}}_{up}$, may be estimated based on pilots sent on the downlink and uplink, respectively, as described below. Estimates of the matrices $\underline{\mathbf{K}}_{ap}$ and $\underline{\mathbf{K}}_{ut}$, which are referred to as correction matrices $\hat{\underline{\mathbf{K}}}_{ap}$ and $\hat{\underline{\mathbf{K}}}_{ut}$, may then be derived based on the downlink and uplink channel response estimates, $\hat{\underline{\mathbf{H}}}_{dn}$ and $\hat{\underline{\mathbf{H}}}_{up}$, as described below. The matrices $\hat{\underline{\mathbf{K}}}_{ap}$ and $\hat{\underline{\mathbf{K}}}_{ut}$ include correction factors that can account for differences in the transmit/receive chains at the access point and user terminal.

[0031] **FIG. 2** illustrates the application of the correction matrices $\hat{\underline{\mathbf{K}}}_{ap}$ and $\hat{\underline{\mathbf{K}}}_{ut}$ to account for differences in the transmit/receive chains at the access point and user terminal. On the downlink, the transmit vector $\underline{\mathbf{x}}_{dn}$ is first multiplied with the matrix $\hat{\underline{\mathbf{K}}}_{ap}$ by a unit 112. The subsequent processing by transmit chain 114 and receive chain 154 for the downlink is the same as shown in FIG. 1. Similarly, on the uplink, the transmit vector $\underline{\mathbf{x}}_{up}$ is first multiplied with the matrix $\hat{\underline{\mathbf{K}}}_{ut}$ by a unit 162. Again, the subsequent processing by transmit chain 164 and receive chain 124 for the uplink is the same as shown in FIG. 1.

[0032] The "calibrated" downlink and uplink channel responses observed by the user terminal and access point, respectively, may then be expressed as:

$$\underline{\mathbf{H}}_{cdn} = \underline{\mathbf{H}}_{dn}\hat{\underline{\mathbf{K}}}_{ap} \quad \text{and} \quad \underline{\mathbf{H}}_{cup} = \underline{\mathbf{H}}_{up}\hat{\underline{\mathbf{K}}}_{ut}, \qquad \text{Eq (7)}$$

where $\underline{\mathbf{H}}_{cdn}^{T}$ and $\underline{\mathbf{H}}_{cup}$ are estimates of the "true" calibrated channel response expressions in equation (6). Combining the two equations in equation set (7) using the expression in equation (6), it can be shown that $\underline{\mathbf{H}}_{cup} \approx \underline{\mathbf{H}}_{cdn}^{T}$. The accuracy of the relationship $\underline{\mathbf{H}}_{cup} \approx \underline{\mathbf{H}}_{cdn}^{T}$ is dependent on the accuracy of the matrices $\hat{\underline{\mathbf{K}}}_{ap}$ and $\hat{\underline{\mathbf{K}}}_{ut}$, which in turn is typically dependent on the quality of the downlink and uplink channel response estimates, $\hat{\underline{\mathbf{H}}}_{dn}$ and $\hat{\underline{\mathbf{H}}}_{up}$.

[0033] As shown above, calibration may be performed in a TDD system to determine the differences in the responses of the transmit/receive chains at the access point and user terminal, and to account for the differences. Once the transmit/receive chains have been calibrated, a calibrated channel response estimate obtained for one link (e.g., $\hat{\underline{\mathbf{H}}}_{cdn}$) may be used to determine an estimate of the calibrated channel response for the other link (e.g., $\hat{\underline{\mathbf{H}}}_{cup}$).

[0034] The calibration techniques described herein may also be used for wireless communication systems that employ OFDM. OFDM effectively partitions the overall system bandwidth into a number of (N_F) orthogonal subbands, which are also referred to as frequency bins or subchannels. With OFDM, each subband is associated with a respective subcarrier upon which data may be modulated. For a MIMO system that

utilizes OFDM (i.e., a MIMO-OFDM system), each subband of each eigenmode may be viewed as an independent transmission channel.

[0035] The calibration may be performed in various manners. For clarity, a specific calibration scheme is described below for a TDD MIMO-OFDM system. For this system, each subband of the wireless link may be assumed to be reciprocal.

[0036] **FIG. 3** is a flow diagram of an embodiment of a process 300 for calibrating the downlink and uplink channel responses in the TDD MIMO-OFDM system. Initially, the user terminal acquires the timing and frequency of the access point using acquisition procedures defined for the system (step 310). The user terminal may then send a message to initiate calibration with the access point, or the calibration may be initiated by the access point. The calibration may be performed in parallel with registration/authentication of the user terminal by the access point (e.g., during call setup) and may also be performed whenever warranted.

[0037] The calibration may be performed for all subbands that may be used for data transmission (which are referred to as the "data" subbands). Subbands not used for data transmission (e.g., guard subbands) typically do not need to be calibrated. However, since the frequency responses of the transmit/receive chains at the access point and user terminal are typically flat over most of the band of interest, and since adjacent subbands are likely to be correlated, the calibration may be performed for only a subset of the data subbands. If fewer than all data subbands are calibrated, then the subbands to be calibrated (which are referred to as the "designated" subbands) may be signaled to the access point (e.g., in the message sent to initiate the calibration).

[0038] For the calibration, the user terminal transmits a MIMO pilot on the designated subbands to the access point (step 312). The generation of the MIMO pilot is described in detail below. The duration of the uplink MIMO pilot transmission may be dependent on the number of designated subbands. For example, 8 OFDM symbols may be sufficient if calibration is performed for four subbands, and more (e.g., 20) OFDM symbols may be needed for more subbands. The total transmit power is typically fixed, so if the MIMO pilot is transmitted on a small number of subbands, then higher amounts of transmit power may be used for each of these subbands and the SNR for each subband is high. Conversely, if the MIMO pilot is transmitted on a large number of subbands then smaller amounts of transmit power may be used for each subband and the SNR for each subband is worse. If the SNR of each subband is not sufficiently high,

then more OFDM symbols may be sent for the MIMO pilot and integrated at the receiver to obtain a higher overall SNR for the subband.

[0039] The access point receives the uplink MIMO pilot and derives an estimate of the uplink channel response, $\underline{\hat{\mathbf{H}}}_{up}(k)$, for each of the designated subbands, where k represents the subband index. Channel estimation based on the MIMO pilot is described below. The uplink channel response estimates are quantized and sent to the user terminal (step 314). The entries in each matrix $\underline{\hat{\mathbf{H}}}_{up}(k)$ are complex channel gains between the N_{ut} transmit and N_{ap} receive antennas for the uplink for the k-th subband. The channel gains for all matrices may be scaled by a particular scaling factor, which is common across all designated subbands, to obtain the desired dynamic range. For example, the channel gains in each matrix $\underline{\hat{\mathbf{H}}}_{up}(k)$ may be inversely scaled by the largest channel gain for all matrices $\underline{\hat{\mathbf{H}}}_{up}(k)$ for the designated subbands so that the largest channel gain is one in magnitude. Since the goal of the calibration is to normalize the gain/phase difference between the downlink and uplink, the absolute channel gains are not important. If 12-bit complex values (i.e., with 12-bit inphase (I) and 12-bit quadrature (Q) components) are used for the channel gains, then the downlink channel response estimates may be sent to the user terminal in $3 \cdot N_{ut} \cdot N_{ap} \cdot N_{sb}$ bytes, where "3" is for the 24 total bits used to represent the I and Q components and N_{sb} is the number of designated subbands.

[0040] The user terminal also receives a downlink MIMO pilot transmitted by the access point (step 316) and derives an estimate of the downlink channel response, $\underline{\hat{\mathbf{H}}}_{dn}(k)$, for each of the designated subbands based on the received pilot (step 318). The user terminal then determines correction factors, $\underline{\hat{\mathbf{K}}}_{ap}(k)$ and $\underline{\hat{\mathbf{K}}}_{ut}(k)$, for each of the designated subbands based on the uplink and downlink channel response estimates, $\underline{\hat{\mathbf{H}}}_{up}(k)$ and $\underline{\hat{\mathbf{H}}}_{dn}(k)$ (step 320).

[0041] For the derivation of the correction factors, the downlink and uplink channel responses for each subband are assumed to be reciprocal, with gain/phase corrections to account for the differences in the transmit/receive chains at the access point and user terminal, as follows:

$$\underline{\mathbf{H}}_{up}(k)\underline{\mathbf{K}}_{ut}(k) = (\underline{\mathbf{H}}_{dn}(k)\underline{\mathbf{K}}_{ap}(k))^{T} \quad , \text{for } k \in K \ , \qquad \text{Eq (8)}$$

where K represents a set with all data subbands. Since only estimates of the effective downlink and uplink channel responses are available for the designated subbands during calibration, equation (8) may be rewritten as:

$$\hat{\underline{\mathbf{H}}}_{up}(k)\hat{\underline{\mathbf{K}}}_{ut}(k) = (\hat{\underline{\mathbf{H}}}_{dn}(k)\hat{\underline{\mathbf{K}}}_{ap}(k))^{T} \quad , \text{for } k \in K' \ , \qquad \text{Eq (9)}$$

where K' represents a set with all designated subbands. A correction vector $\hat{\underline{\mathbf{k}}}_{ut}(k)$ may be defined to include only the N_{ut} diagonal elements of $\hat{\underline{\mathbf{K}}}_{ut}(k)$. Similarly, a correction vector $\hat{\underline{\mathbf{k}}}_{ap}(k)$ may be defined to include only the N_{ap} diagonal elements of $\hat{\underline{\mathbf{K}}}_{ap}(k)$.

[0042] The correction factors $\hat{\underline{\mathbf{K}}}_{ap}(k)$ and $\hat{\underline{\mathbf{K}}}_{ut}(k)$ may be derived from the channel estimates $\hat{\underline{\mathbf{H}}}_{dn}(k)$ and $\hat{\underline{\mathbf{H}}}_{up}(k)$ in various manners, including by a matrix-ratio computation and a minimum mean square error (MMSE) computation. Both of these computation methods are described in further detail below. Other computation methods may also be used, and this is within the scope of the invention.

A. Matrix-Ratio Computation

[0043] **FIG. 4** is a flow diagram of an embodiment of a process 320a for deriving the correction vectors $\hat{\underline{\mathbf{k}}}_{ut}(k)$ and $\hat{\underline{\mathbf{k}}}_{ap}(k)$ from the downlink and uplink channel response estimates $\hat{\underline{\mathbf{H}}}_{up}(k)$ and $\hat{\underline{\mathbf{H}}}_{dn}(k)$ using matrix-ratio computation. Process 320a may be used for step 320 in FIG. 3.

[0044] Initially, an $(N_{ut} \times N_{ap})$ matrix $\underline{\mathbf{C}}(k)$ is computed for each designated subband (step 412), as follows:

$$\underline{\mathbf{C}}(k) = \frac{\hat{\underline{\mathbf{H}}}_{up}^{T}(k)}{\hat{\underline{\mathbf{H}}}_{dn}(k)} \quad , \text{ for } k \in K' \ , \qquad \text{Eq (10)}$$

where the ratio is taken element-by-element. Each element of $\underline{\mathbf{C}}(k)$ may thus be computed as:

$$c_{i,j}(k) = \frac{\hat{h}_{up\,i,j}(k)}{\hat{h}_{dn\,i,j}(k)} \quad , \text{ for } i = \{1 \ldots N_{ut}\} \text{ and } j = \{1 \ldots N_{ap}\} , \qquad \text{Eq (11)}$$

where $\hat{h}_{\text{up}\,i,j}(k)$ and $\hat{h}_{\text{dn}\,i,j}(k)$ are the (i,j)-th (row, column) element of $\underline{\hat{\mathbf{H}}}^{T}_{\text{up}}(k)$ and $\underline{\hat{\mathbf{H}}}_{\text{dn}}(k)$, respectively, and $c_{i,j}(k)$ is the (i,j)-th element of $\underline{\mathbf{C}}(k)$.

[0045] In an embodiment, the correction vector for the access point, $\underline{\hat{\mathbf{k}}}_{\text{ap}}(k)$, is defined to be equal to the mean of the normalized rows of $\underline{\mathbf{C}}(k)$ and is derived by the steps in block 420. Each row of $\underline{\mathbf{C}}(k)$ is first normalized by scaling each of the N_{ap} elements in the row with the first element in the row (step 422). Thus, if $\underline{\mathbf{c}}_i(k) = [c_{i,1}(k) \ \ldots \ c_{i,N_{ap}}(k)]$ is the i-th row of $\underline{\mathbf{C}}(k)$, then the normalized row $\underline{\tilde{\mathbf{c}}}_i(k)$ may be expressed as:

$$\underline{\tilde{\mathbf{c}}}_i(k) = [c_{i,1}(k)/c_{i,1}(k) \ \ldots \ c_{i,j}(k)/c_{i,1}(k) \ \ldots \ c_{i,N_{ap}}(k)/c_{i,1}(k)] \ . \qquad \text{Eq (12)}$$

The mean of the normalized rows is then determined as the sum of the N_{ut} normalized rows divided by N_{ut} (step 424). The correction vector $\underline{\hat{\mathbf{k}}}_{\text{ap}}(k)$ is set equal to this mean (step 426), which may be expressed as:

$$\underline{\hat{\mathbf{k}}}_{\text{ap}}(k) = \frac{1}{N_{ut}} \sum_{i=1}^{N_{ut}} \underline{\tilde{\mathbf{c}}}_i(k) \ , \text{ for } k \in K' . \qquad \text{Eq (13)}$$

Because of the normalization, the first element of $\underline{\hat{\mathbf{k}}}_{\text{ap}}(k)$ is unity.

[0046] In an embodiment, the correction vector for the user terminal, $\underline{\hat{\mathbf{k}}}_{\text{ut}}(k)$, is defined to be equal to the mean of the inverses of the normalized columns of $\underline{\mathbf{C}}(k)$ and is derived by the steps in block 430. The j-th column of $\underline{\mathbf{C}}(k)$ is first normalized by scaling each element in the column with the j-th element of the vector $\underline{\hat{\mathbf{k}}}_{\text{ap}}(k)$, which is denoted as $K_{\text{ap},j,j}(k)$ (step 432). Thus, if $\underline{\mathbf{c}}_j(k) = [c_{1,j}(k) \ \ldots \ c_{N_{ut},j}(k)]^T$ is the j-th column of $\underline{\mathbf{C}}(k)$, then the normalized column $\underline{\breve{\mathbf{c}}}_j(k)$ may be expressed as:

$$\underline{\breve{\mathbf{c}}}_j(k) = [c_{1,j}(k)/K_{\text{ap},j,j}(k) \ \ldots \ c_{i,j}(k)/K_{\text{ap},j,j}(k) \ \ldots \ c_{N_{ut},j}(k)/K_{\text{ap},j,j}(k)]^T \ . \qquad \text{Eq (14)}$$

The mean of the inverses of the normalized columns is then determined as the sum of the inverses of the N_{ap} normalized columns divided by N_{ap} (step 434). The correction vector $\underline{\hat{\mathbf{k}}}_{\text{ut}}(k)$ is set equal to this mean (step 436), which may be expressed as:

$$\underline{\hat{\mathbf{k}}}_{\text{ut}}(k) = \frac{1}{N_{ap}} \sum_{j=1}^{N_{ap}} \frac{1}{\underline{\breve{\mathbf{c}}}_j(k)} \ , \text{ for } k \in K , \qquad \text{Eq (15)}$$

where the inversion of the normalized columns, $\breve{\underline{c}}_j(k)$, is performed element-wise.

B. MMSE Computation

[0047] For the MMSE computation, the correction factors $\hat{\underline{K}}_{ap}(k)$ and $\hat{\underline{K}}_{ut}(k)$ are derived from the downlink and uplink channel response estimates $\hat{\underline{H}}_{dn}(k)$ and $\hat{\underline{H}}_{up}(k)$ such that the mean square error (MSE) between the calibrated downlink channel response and the calibrated uplink channel response is minimized. This condition may be expressed as:

$$\min \left| (\hat{\underline{H}}_{dn}(k)\hat{\underline{K}}_{ap}(k))^T - \hat{\underline{H}}_{up}(k)\hat{\underline{K}}_{ut}(k) \right|^2 , \text{ for } k \in K, \qquad \text{Eq (16)}$$

which may also be written as:

$$\min \left| \hat{\underline{K}}_{ap}(k)\hat{\underline{H}}_{dn}^T(k) - \hat{\underline{H}}_{up}(k)\hat{\underline{K}}_{ut}(k) \right|^2 , \text{ for } k \in K,$$

where $\hat{\underline{K}}_{ap}^T(k) = \hat{\underline{K}}_{ap}(k)$ since $\hat{\underline{K}}_{ap}(k)$ is a diagonal matrix.

[0048] Equation (16) is subject to the constraint that the lead element of $\hat{\underline{K}}_{ap}(k)$ is set equal to unity (i.e., $\hat{\underline{K}}_{ap,0,0}(k) = 1$). Without this constraint, the trivial solution would be obtained with all elements of the matrices $\hat{\underline{K}}_{ap}(k)$ and $\hat{\underline{K}}_{ut}(k)$ set equal to zero. In equation (16), a matrix $\underline{Y}(k)$ is first obtained as $\underline{Y}(k) = \hat{\underline{K}}_{ap}(k)\hat{\underline{H}}_{dn}^T(k) - \hat{\underline{H}}_{up}(k)\hat{\underline{K}}_{ut}(k)$. The square of the absolute value is next obtained for each of the $N_{ap} \cdot N_{ut}$ entries of the matrix $\underline{Y}(k)$. The mean square error (or the square error, since a divide by $N_{ap} \cdot N_{ut}$ is omitted) is then equal to the sum of all $N_{ap} \cdot N_{ut}$ squared values.

[0049] The MMSE computation is performed for each designated subband to obtain the correction factors $\hat{\underline{K}}_{ap}(k)$ and $\hat{\underline{K}}_{ut}(k)$ for that subband. The MMSE computation for one subband is described below. For simplicity, the subband index, k, is omitted in the following description. Also for simplicity, the elements of the downlink channel response estimate $\hat{\underline{H}}_{dn}^T$ are denoted as $\{a_{ij}\}$, the elements of the uplink channel response estimate $\hat{\underline{H}}_{up}$ are denoted as $\{b_{ij}\}$, the diagonal elements of the matrix $\hat{\underline{K}}_{ap}$ are denoted

as $\{u_i\}$, and the diagonal elements of the matrix $\underline{\hat{\mathbf{K}}}_{ut}$ are denoted as $\{v_j\}$, where $i=\{1 \ldots N_{ap}\}$ and $j=\{1 \ldots N_{ut}\}$.

[0050] The mean square error may be rewritten from equation (16), as follows:

$$\mathrm{MSE}=\sum_{j=1}^{N_{ut}}\sum_{i=1}^{N_{ap}}|a_{ij}u_i-b_{ij}v_j|^2 \quad , \qquad \text{Eq (17)}$$

again subject to the constraint $u_1=1$. The minimum mean square error may be obtained by taking the partial derivatives of equation (17) with respect to u and v and setting the partial derivatives to zero. The results of these operations are the following equation sets:

$$\sum_{j=1}^{N_{ut}}(a_{ij}u_i-b_{ij}v_j)\cdot a_{ij}^*=0 \quad , \text{for } i\in\{2 \ldots N_{ap}\}, \text{ and} \qquad \text{Eq (18a)}$$

$$\sum_{i=1}^{N_{ap}}(a_{ij}u_i-b_{ij}v_j)\cdot b_{ij}^*=0 \quad , \text{for } j\in\{1 \ldots N_{ut}\}. \qquad \text{Eq (18b)}$$

In equation (18a), $u_1=1$ so there is no partial derivative for this case, and the index i runs from 2 through N_{ap}.

[0051] The set of $(N_{ap}+N_{ut}-1)$ equations in equation sets (18a) and (18b) may be more conveniently expressed in matrix form, as follows:

$$\underline{\mathbf{A}}\underline{\mathbf{y}}=\underline{\mathbf{z}} \quad , \qquad \text{Eq (19)}$$

where

$$\underline{\mathbf{A}} = \begin{bmatrix} \sum_{j=1}^{N_{ut}} |a_{2j}|^2 & 0 & \cdots & 0 & -b_{21}a_{21}^* & \cdots & -b_{2N_{ap}}a_{2N_{ut}}^* \\ 0 & \sum_{j=1}^{N_{ut}} |a_{3j}|^2 & 0 & \cdots & \cdots & \cdots & \cdots \\ \cdots & 0 & \cdots & 0 & & & \\ 0 & \cdots & 0 & \sum_{j=1}^{N_{ut}} |a_{N_{ap}j}|^2 & -b_{N_{ap}1}a_{N_{ap}1}^* & & -b_{N_{ap}N_{ut}}a_{N_{ap}N_{ut}}^* \\ -a_{21}b_{21}^* & \cdots & & -a_{N_{ap}1}b_{N_{ap}1}^* & \sum_{i=1}^{N_{ap}} |b_{i1}|^2 & 0 \quad \cdots \quad 0 & \\ \cdots & \cdots & & & 0 & \sum_{i=1}^{N_{ap}} |b_{i2}|^2 \quad 0 \quad \cdots & \\ & & & & \cdots & 0 \quad \cdots \quad 0 & \\ -a_{2N_{ut}}b_{2N_{ut}}^* & \cdots & & -a_{N_{ap}N_{ut}}b_{N_{ap}N_{ut}}^* & 0 & \cdots \quad 0 & \sum_{i=1}^{N_{ap}} |b_{iN_{ut}}|^2 \end{bmatrix}$$

$$\underline{\mathbf{y}} = \begin{bmatrix} u_2 \\ u_3 \\ \cdots \\ u_{N_{ap}} \\ v_1 \\ v_2 \\ \cdots \\ v_{N_{ut}} \end{bmatrix} \text{ and } \underline{\mathbf{z}} = \begin{bmatrix} 0 \\ 0 \\ \cdots \\ 0 \\ a_{11}b_{11}^* \\ a_{12}b_{12}^* \\ \cdots \\ a_{1N_{ut}}b_{1N_{ut}}^* \end{bmatrix}.$$

[0052] The matrix $\underline{\mathbf{A}}$ includes $(N_{ap} + N_{ut} - 1)$ rows, with the first $N_{ap} - 1$ rows corresponding to the $N_{ap} - 1$ equations from equation set (18a) and the last N_{ut} rows corresponding to the N_{ut} equations from equation set (18b). In particular, the first row of the matrix $\underline{\mathbf{A}}$ is generated from equation set (18a) with $i = 2$, the second row is generated with $i = 3$, and so on. The N_{ap}-th row of the matrix $\underline{\mathbf{A}}$ is generated from equation set (18b) with $j = 1$, and so on, and the last row is generated with $j = N_{ut}$. As shown above, the entries of the matrix $\underline{\mathbf{A}}$ and the entries of the vector $\underline{\mathbf{z}}$ may be obtained based on the entries in the matrices $\underline{\hat{\mathbf{H}}}_{\text{dn}}^T$ and $\underline{\hat{\mathbf{H}}}_{\text{up}}$.

[0053] The correction factors are included in the vector $\underline{\mathbf{y}}$, which may be obtained as:

$$\underline{\mathbf{y}} = \underline{\mathbf{A}}^{-1}\underline{\mathbf{z}} \quad . \qquad \text{Eq (20)}$$

[0054] The results of the MMSE computation are correction matrices $\underline{\hat{K}}_{ap}$ and $\underline{\hat{K}}_{ut}$ that minimize the mean square error in the calibrated downlink and uplink channel responses, as shown in equation (16). Since the matrices $\underline{\hat{K}}_{ap}$ and $\underline{\hat{K}}_{ut}$ are obtained based on the downlink and uplink channel response estimates, $\underline{\hat{H}}_{dn}$ and $\underline{\hat{H}}_{up}$, the quality of the correction matrices $\underline{\hat{K}}_{ap}$ and $\underline{\hat{K}}_{ut}$ are thus dependent on the quality of the channel estimates $\underline{\hat{H}}_{dn}$ and $\underline{\hat{H}}_{up}$. The MIMO pilot may be averaged at the receiver to obtain more accurate estimates for $\underline{\hat{H}}_{dn}$ and $\underline{\hat{H}}_{up}$.

[0055] The correction matrices, $\underline{\hat{K}}_{ap}$ and $\underline{\hat{K}}_{ut}$, obtained based on the MMSE computation are generally better than the correction matrices obtained based on the matrix-ratio computation, especially when some of the channel gains are small and measurement noise can greatly degrade the channel gains.

C. Post Computation

[0056] Regardless of the particular computation method selected for use, after completion of the computation of the correction matrices, the user terminal sends to the access point the correction vectors for the access point, $\underline{\hat{k}}_{ap}(k)$, for all designated subbands. If 12-bit complex values are used for each correction factor in $\underline{\hat{k}}_{ap}(k)$, then the correction vectors $\underline{\hat{k}}_{ap}(k)$ for all designated subbands may be sent to the access point in $3 \cdot (N_{ap} - 1) \cdot N_{sb}$ bytes, where "3" is for the 24 total bits used for the I and Q components and $(N_{ap} - 1)$ results from the first element in each vector $\underline{\hat{k}}_{ap}(k)$ being equal to unity and thus not needing to be sent. If the first element is set to $2^9 - 1 = +511$, then 12 dB of headroom is available (since the maximum positive 12-bit signed value is $2^{11} - 1 = +2047$), which would then allow gain mismatch of up to 12 dB between the downlink and uplink to be accommodated by 12-bit values. If the downlink and uplink match to within 12 dB and the first element is normalized to a value of 511, then the other elements should be no greater than $511 \cdot 4 = 2044$ in absolute value and can be represented with 12 bits.

[0057] A pair of correction vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$ and $\hat{\underline{\mathbf{k}}}_{ut}(k)$ is obtained for each designated subband. If the calibration is performed for fewer than all of the data subbands, then the correction factors for the "uncalibrated" subbands may be obtained by interpolating the correction factors obtained for the designated subbands. The interpolation may be performed by the access point to obtain the correction vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$, for $k \in K$. Similarly, the interpolation may be performed by the user terminal to obtain the correction vectors $\hat{\underline{\mathbf{k}}}_{ut}(k)$, for $k \in K$.

[0058] The access point and user terminal thereafter use their respective correction vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$ and $\hat{\underline{\mathbf{k}}}_{ut}(k)$, or the corresponding correction matrices $\hat{\underline{\mathbf{K}}}_{ap}(k)$ and $\hat{\underline{\mathbf{K}}}_{ut}(k)$, for $k \in K$, to scale modulation symbols prior to transmission over the wireless channel, as described below. The effective downlink channel that the user terminal sees would then be $\underline{\mathbf{H}}_{cdn}(k) = \underline{\mathbf{H}}_{dn}(k)\hat{\underline{\mathbf{K}}}_{ap}(k)$.

[0059] The calibration scheme described above, whereby a vector of correction factors is obtained for each of the access point and user terminal, allows "compatible" correction vectors to be derived for the access point when the calibration is performed by different user terminals. If the access point has already been calibrated (e.g., by one or more other user terminals), then the current correction vectors may be updated with the newly derived correction vectors.

[0060] For example, if two user terminals simultaneously perform the calibration procedure, then the calibration results from these user terminals may be averaged to improve performance. However, calibration is typically performed for one user terminal at a time. So the second user terminal observes the downlink with the correction vector for the first user terminal already applied. In this case, the product of the second correction vector with the old correction vector may be used as the new correction vector, or a "weighted averaging" (described below) may also be used. The access point typically uses a single correction vector for all user terminals, and not different ones for different user terminals (although this may also be implemented). Updates from multiple user terminals or sequential updates from one user terminal may be treated in the same manner. The updated vectors may be directly applied (by a product operation). Alternatively, if some averaging is desired to reduce measurement noise, then weighted averaging may be used as described below.

[0061] Thus, if the access point uses correction vectors $\hat{\underline{\mathbf{k}}}_{ap1}(k)$ to transmit the MIMO pilot from which the user terminal determines new correction vectors $\hat{\underline{\mathbf{k}}}_{ap2}(k)$, then the updated correction vectors $\hat{\underline{\mathbf{k}}}_{ap3}(k)$ are the product of the current and new correction vectors. The correction vectors $\hat{\underline{\mathbf{k}}}_{ap1}(k)$ and $\hat{\underline{\mathbf{k}}}_{ap2}(k)$ may be derived by the same or different user terminals.

[0062] In one embodiment, the updated correction vectors are defined as $\hat{\underline{\mathbf{k}}}_{ap3}(k) = \hat{\underline{\mathbf{k}}}_{ap1}(k) \cdot \hat{\underline{\mathbf{k}}}_{ap2}(k)$, where the multiplication is element-by-element. In another embodiment, the updated correction vectors may be redefined as $\hat{\underline{\mathbf{k}}}_{ap3}(k) = \hat{\underline{\mathbf{k}}}_{ap1}(k) \cdot \hat{\underline{\mathbf{k}}}^{\alpha}_{ap2}(k)$, where α is a factor used to provide weighted averaging (e.g., $0 < \alpha < 1$). If the calibration updates are infrequent, then □ close to one might perform best. If the calibration updates are frequent but noisy, then a smaller value for □ is better. The updated correction vectors $\hat{\underline{\mathbf{k}}}_{ap3}(k)$ may then be used by the access point until they are updated again.

[0063] As noted above, the calibration may be performed for fewer than all data subbands. For example, the calibration may be performed for every n-th subband, where n may be determined by the expected response of the transmit/receive chains (e.g., n may be 2, 4, 8, 16, and so on). The calibration may also be performed for non-uniformly distributed subbands. For example, since there may be more filter roll-off at the edges of the passband, which may create more mismatch in the transmit/receive chains, more subbands near the band edges may be calibrated. In general, any number and any distribution of subbands may be calibrated, and this is within the scope of the invention.

[0064] In the above description, the correction vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$ and $\hat{\underline{\mathbf{k}}}_{ut}(k)$, for $k \in K'$, are derived by the user terminal, and the vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$ are sent back to the access point. This scheme advantageously distributes the calibration processing among the user terminals for a multiple-access system. However, the correction vectors $\hat{\underline{\mathbf{k}}}_{ap}(k)$ and $\hat{\underline{\mathbf{k}}}_{ut}(k)$ may also be derived by the access point, which would then send the vectors $\hat{\underline{\mathbf{k}}}_{ut}(k)$ back to the user terminal, and this is within the scope of the invention.

[0065] The calibration scheme described above allows each user terminal to calibrate its transmit/receive chains in real-time via over-the-air transmission. This allows user terminals with different frequency responses to achieve high performance without the need for tight frequency response specifications or to perform calibration at the factory. The access point may be calibrated by multiple user terminals to provide improved accuracy.

D. Gain Considerations

[0066] The calibration may be performed based on "normalized" gains for the downlink and uplink channels, which are gains given relative to the noise floor at the receiver. The use of the normalized gains allows the characteristics of one link (including the channel gains and SNR per eigenmode) to be obtained based on gain measurements for the other link, after the downlink and uplink have been calibrated.

[0067] The access point and user terminal may initially balance their receiver input levels such that the noise levels on the receive paths for the access point and user terminal are approximately the same. The balancing may be done by estimating the noise floor, that is, finding a section of a received TDD frame (i.e., a unit of downlink/uplink transmission) that has a minimum average power over a particular time duration (e.g., one or two symbol periods). Generally, the time just before the start of each TDD frame is clear of transmissions, since any uplink data needs to be received by the access point and then a receive/transmit turnaround time is necessary before the access point transmits on the downlink. Depending on the interference environment, the noise floor may be determined based on a number of TDD frames. The downlink and uplink channel responses are then measured relative to this noise floor. More specifically, the channel gain for a given subband of a given transmit/receive antenna pair may first be obtained, for example, as the ratio of the received pilot symbol over the transmitted pilot symbol for that subband of that transmit/receive antenna pair. The normalized gain is then the measured gain divided by the noise floor.

[0068] A large difference in the normalized gains for the access point and the normalized gains for the user terminal can result in the correction factors for the user terminal being greatly different from unity. The correction factors for the access point are close to unity because the first element of the matrix $\hat{\underline{\mathbf{K}}}_{ap}$ is set to 1.

[0069] If the correction factors for the user terminal differ greatly from unity, then the user terminal may not be able to apply the computed correction factors. This is because the user terminal has a constraint on its maximum transmit power and may not be capable of increasing its transmit power for large correction factors. Moreover, a reduction in transmit power for small correction factors is generally not desirable, since this may reduce the achievable data rate.

[0070] Thus, the user terminal can transmit using a scaled version of the computed correction factors. The scaled calibration factors may be obtained by scaling the computed correction factors by a particular scaling value, which may be set equal to a gain delta (difference or ratio) between the downlink and uplink channel responses. This gain delta can be computed as an average of the differences (or deltas) between the normalized gains for the downlink and uplink. The scaling value (or gain delta) used for the correction factors for the user terminal can be sent to the access point along with the computed correction factors for the access point.

[0071] With the correction factors and the scaling value or gain delta, the downlink channel characteristics may be determined from the measured uplink channel response, and vice versa. If the noise floor at either the access point or the user terminal changes, then the gain delta can be updated, and the updated gain delta may be sent in a message to the other entity.

[0072] In the above description, the calibration results in two sets (or vectors or matrices) of correction factors for each subband, with one set being used by the access point for downlink data transmission and the other set being used by the user terminal for uplink data transmission. The calibration may also be performed such that two sets of correction factors are provided for each subband, with one set being used by the access point for uplink data reception and the other set being used by the user terminal for downlink data reception. The calibration may also be performed such that one set of correction factors is obtained for each subband, and this set may be used at either the access point or the user terminal. In general, the calibration is performed such that the calibrated downlink and uplink channel responses are reciprocal, regardless of where correction factors are applied.

2. MIMO Pilot

[0073] For the calibration, a MIMO pilot is transmitted on the uplink by the user terminal to allow the access point to estimate the uplink channel response, and a MIMO pilot is transmitted on the downlink by the access point to allow the user terminal to estimate the downlink channel response. The same or different MIMO pilots may be used for the downlink and uplink, and the MIMO pilots used are known at both the access point and user terminal.

[0074] In an embodiment, the MIMO pilot comprises a specific OFDM symbol (denoted as "P") that is transmitted from each of the N_T transmit antennas, where $N_T = N_{ap}$ for the downlink and $N_T = N_{ut}$ for the uplink. For each transmit antenna, the same P OFDM symbol is transmitted in each symbol period designated for MIMO pilot transmission. However, the P OFDM symbols for each antenna are covered with a different N-chip Walsh sequence assigned to that antenna, where $N \geq N_{ap}$ for the downlink and $N \geq N_{ut}$ for the uplink. The Walsh covering maintains orthogonality between the N_T transmit antennas and allows the receiver to distinguish the individual transmit antennas.

[0075] The P OFDM symbol includes one modulation symbol for each of the N_{sb} designated subbands. The P OFDM symbol thus comprises a specific "word" of N_{sb} modulation symbols that may be selected to facilitate channel estimation by the receiver. This word may also be defined to minimize the peak-to-average variation in the transmitted MIMO pilot. This may then reduce the amount of distortion and non-linearity generated by the transmit/receive chains, which may then result in improved accuracy for the channel estimation.

[0076] For clarity, a specific MIMO pilot is described below for a specific MIMO-OFDM system. For this system, the access point and user terminal each has four transmit/receive antennas. The system bandwidth is partitioned into 64 orthogonal subbands (i.e., $N_F = 64$), which are assigned indices of +31 to -32. Of these 64 subbands, 48 subbands (e.g., with indices of $\pm\{1, \ldots, 6, 8, \ldots, 20, 22, \ldots, 26\}$) are used for data, 4 subbands (e.g., with indices of $\pm\{7, 21\}$) are used for pilot and possibly signaling, the DC subband (with index of 0) is not used, and the remaining subbands are also not used and serve as guard subbands. This OFDM subband structure is described

in further detail in a document for IEEE Standard 802.11a and entitled "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHz Band," September 1999, which is publicly available and incorporated herein by reference.

[0077] The P OFDM symbol includes a set of 52 QPSK modulation symbols for the 48 data subbands and 4 pilot subbands. This P OFDM symbol may be given as follows:

$$P(\text{real}) = g \cdot \{0,0,0,0,0,0,-1,-1,-1,-1,1,1,1,-1,-1,1,-1,1,1,1,1,1,-1,-1,1,-1,1,-1,-1,-1,-1,1,-1,$$
$$0,1,-1,-1,-1,-1,1,-1,-1,-1,-1,1,1,-1,-1,1,-1,-1,1,1,-1,1,-1,1,-1,1,-,0,0,0,0,0\},$$
$$P(\text{imag}) = g \cdot \{0,0,0,0,0,0,-1,1,1,1,-1,-1,1,-1,1,1,1,-1,1,-1,-1,-1,-1,-1,-1,1,1,-1,1,1,-1,1,$$
$$0,-1,-1,-1,-1,1,1,-1,1,-1,-1,1,-1,1,-1,1,1,1,-1,1,1,1,1,1,1,-1,-1,0,0,0,0,0\},$$

where g is a gain for the pilot. The values within the { } bracket are given for subband indices -32 through -1 (for the first line) and 0 through +31 (for the second line). Thus, the first line for P(real) and P(imag) indicates that symbol $(-1-j)$ is transmitted in subband -26, symbol $(-1+j)$ is transmitted in subband -25, and so on. The second line for P(real) and P(imag) indicates that symbol $(1-j)$ is transmitted in subband 1, symbol $(-1-j)$ is transmitted in subband 2, and so on. Other OFDM symbols may also be used for the MIMO pilot.

[0078] In an embodiment, the four transmit antennas are assigned Walsh sequences of $W_1 = 1111$, $W_2 = 1010$, $W_3 = 1100$, and $W_4 = 1001$ for the MIMO pilot. For a given Walsh sequence, a value of "1" indicates that a P OFDM symbol is transmitted and a value of "0" indicates that a -P OFDM symbol is transmitted (i.e., each of the 52 modulation symbols in P is inverted).

[0079] Table 1 lists the OFDM symbols transmitted from each of the four transmit antennas for a MIMO pilot transmission that spans four symbol periods.

Table 1

OFDM symbol	Antenna 1	Antenna 2	Antenna 3	Antenna 4
1	+P	+P	+P	+P
2	+P	-P	+P	-P
3	+P	+P	-P	-P
4	+P	-P	-P	+P

For longer MIMO pilot transmission, the Walsh sequence for each transmit antenna is simply repeated. For this set of Walsh sequences, the MIMO pilot transmission occurs in integer multiples of four symbol periods to ensure orthogonality among the four transmit antennas.

[0080] The receiver may derive an estimate of the channel response based on the received MIMO pilot by performing the complementary processing. In particular, to recover the pilot sent from transmit antenna *i* and received by receive antenna *j*, the pilot received by receive antenna *j* is first processed with the Walsh sequence assigned to transmit antenna *i* in a complementary manner to the Walsh covering performed at the transmitter. The decovered OFDM symbols for all N_{ps} symbol periods for the MIMO pilot are then accumulated, where the accumulation is performed individually for each of the 52 subbands used to carry the MIMO pilot. The results of the accumulation is $\hat{h}_{i,j}(k)$, for $k = \pm\{1, ..., 26\}$, which is an estimate of the effective channel response from transmit antenna *i* to receive antenna *j* (i.e., including the responses for the transmit/receive chains) for the 52 data and pilot subbands.

[0081] The same processing may be performed to recover the pilot from each transmit antenna at each receive antenna. The pilot processing provides $N_{ap} \cdot N_{ut}$ values that are the elements of the effective channel response estimate, $\underline{\hat{\mathbf{H}}}_{\text{up}}(k)$ or $\underline{\hat{\mathbf{H}}}_{\text{dn}}(k)$, for each of the 52 subbands.

[0082] The channel estimation described above may be performed by both the access point and the user terminal during calibration to obtain the effective uplink channel response estimate $\underline{\hat{\mathbf{H}}}_{\text{up}}(k)$ and the effective downlink channel response estimate $\underline{\hat{\mathbf{H}}}_{\text{dn}}(k)$, respectively, which are then used to derive the correction factors as described above.

3. Spatial Processing

[0083] The correlation between the downlink and uplink channel responses may be exploited to simplify the channel estimation and spatial processing at the access point and user terminal for TDD MIMO and MIMO-OFDM systems. This simplification is

possible after calibration has been performed to account for differences in the transmit/receive chains. As noted above, the calibrated channel responses are:

$$\underline{\mathbf{H}}_{\text{cdn}}(k) = \underline{\mathbf{H}}_{\text{dn}}(k)\hat{\underline{\mathbf{K}}}_{\text{ap}}(k), \quad \text{for the downlink, and} \quad \text{Eq (21a)}$$

$$\underline{\mathbf{H}}_{\text{cup}}(k) = (\underline{\mathbf{H}}_{\text{dn}}(k)\hat{\underline{\mathbf{K}}}_{\text{ap}}(k))^T \cong \underline{\mathbf{H}}_{\text{up}}(k)\hat{\underline{\mathbf{K}}}_{\text{ut}}(k), \text{ for the uplink.} \quad \text{Eq (21b)}$$

The last equality in equation (21b) comes from using the relationship between the effective downlink and uplink channel responses, $\underline{\mathbf{H}}_{\text{up}}(k) = (\underline{\mathbf{K}}_{\text{ut}}^{-1}(k)\underline{\mathbf{H}}_{\text{dn}}(k)\underline{\mathbf{K}}_{\text{ap}}(k))^T$.

[0084] The channel response matrix $\underline{\mathbf{H}}(k)$ for each subband may be "diagonalized" to obtain the N_S eigenmodes for that subband. This may be achieved by performing either singular value decomposition on the channel response matrix $\underline{\mathbf{H}}(k)$ or eigenvalue decomposition on the correlation matrix of $\underline{\mathbf{H}}(k)$, which is $\underline{\mathbf{R}}(k) = \underline{\mathbf{H}}^H(k)\underline{\mathbf{H}}(k)$.

[0085] The singular value decomposition of the calibrated uplink channel response matrix, $\underline{\mathbf{H}}_{\text{cup}}(k)$, may be expressed as:

$$\underline{\mathbf{H}}_{\text{cup}}(k) = \underline{\mathbf{U}}_{\text{ap}}(k)\underline{\Sigma}(k)\underline{\mathbf{V}}_{\text{ut}}^H(k) \quad \text{, for } k \in K, \quad \text{Eq (22)}$$

where $\underline{\mathbf{U}}_{\text{ap}}(k)$ is an $(N_{ut} \times N_{ut})$ unitary matrix of left eigenvectors of $\underline{\mathbf{H}}_{\text{cup}}(k)$;

$\underline{\Sigma}(k)$ is an $(N_{ut} \times N_{ap})$ diagonal matrix of singular values of $\underline{\mathbf{H}}_{\text{cup}}(k)$; and

$\underline{\mathbf{V}}_{\text{ut}}(k)$ is an $(N_{ap} \times N_{ap})$ unitary matrix of right eigenvectors of $\underline{\mathbf{H}}_{\text{cup}}(k)$.

[0086] A unitary matrix $\mathbf{M}$ is characterized by the property $\underline{\mathbf{M}}^H\underline{\mathbf{M}} = \underline{\mathbf{I}}$, where $\underline{\mathbf{I}}$ is the identity matrix. Correspondingly, the singular value decomposition of the calibrated downlink channel response matrix, $\underline{\mathbf{H}}_{\text{cdn}}(k)$, may be expressed as:

$$\underline{\mathbf{H}}_{\text{cdn}}(k) = \underline{\mathbf{V}}_{\text{ut}}^*(k)\underline{\Sigma}(k)\underline{\mathbf{U}}_{\text{ap}}^T(k) \quad \text{, for } k \in K. \quad \text{Eq (23)}$$

The matrices $\underline{\mathbf{V}}_{\text{ut}}^*(k)$ and $\underline{\mathbf{U}}_{\text{ap}}^T(k)$ are thus also matrices of left and right eigenvectors, respectively, of $\underline{\mathbf{H}}_{\text{cdn}}(k)$. The matrices $\underline{\mathbf{V}}_{\text{ut}}(k)$, $\underline{\mathbf{V}}_{\text{ut}}^*(k)$, $\underline{\mathbf{V}}_{\text{ut}}^T(k)$, and $\underline{\mathbf{V}}_{\text{ut}}^H(k)$ are different forms of the matrix $\underline{\mathbf{V}}_{\text{ut}}(k)$, and the matrices $\underline{\mathbf{U}}_{\text{ap}}(k)$, $\underline{\mathbf{U}}_{\text{ap}}^*(k)$, $\underline{\mathbf{U}}_{\text{ap}}^T(k)$, and $\underline{\mathbf{U}}_{\text{ap}}^H(k)$ are also different forms of the matrix $\underline{\mathbf{U}}_{\text{ap}}(k)$. For simplicity, reference to the matrices $\underline{\mathbf{U}}_{\text{ap}}(k)$ and $\underline{\mathbf{V}}_{\text{ut}}(k)$ in the following description may also refer to their various other forms. The matrices $\underline{\mathbf{U}}_{\text{ap}}(k)$ and $\underline{\mathbf{V}}_{\text{ut}}(k)$ are used by the access point and user terminal, respectively, for spatial processing and are denoted as such by their subscripts.

[0087] The singular value decomposition is described in further detail by Gilbert Strang entitled "Linear Algebra and Its Applications," Second Edition, Academic Press, 1980.

[0088] The user terminal can estimate the calibrated downlink channel response based on a MIMO pilot sent by the access point. The user terminal may then perform the singular value decomposition of the calibrated downlink channel response estimate $\underline{\hat{\mathbf{H}}}_{\text{cdn}}(k)$, for $k \in K$, to obtain the diagonal matrices $\underline{\hat{\Sigma}}(k)$ and the matrices $\underline{\mathbf{V}}^{*}_{\text{ut}}(k)$ of left eigenvectors of $\underline{\hat{\mathbf{H}}}_{\text{cdn}}(k)$. This singular value decomposition may be given as $\underline{\hat{\mathbf{H}}}_{\text{cdn}}(k) = \underline{\hat{\mathbf{V}}}^{*}_{\text{ut}}(k)\underline{\hat{\Sigma}}(k)\underline{\hat{\mathbf{U}}}^{T}_{\text{ap}}(k)$, where the hat ("^") above each matrix indicates that it is an estimate of the actual matrix.

[0089] Similarly, the access point can estimate the calibrated uplink channel response based on a MIMO pilot sent by the user terminal. The access point may then perform the singular value decomposition of the calibrated uplink channel response estimate $\underline{\hat{\mathbf{H}}}_{\text{cup}}(k)$, for $k \in K$, to obtain the diagonal matrices $\underline{\hat{\Sigma}}(k)$ and the matrices $\underline{\hat{\mathbf{U}}}_{\text{ap}}(k)$ of left eigenvectors of $\underline{\hat{\mathbf{H}}}_{\text{cup}}(k)$, for $k \in K$. This singular value decomposition may be given as $\underline{\hat{\mathbf{H}}}_{\text{cup}}(k) = \underline{\hat{\mathbf{U}}}_{\text{ap}}(k)\underline{\hat{\Sigma}}(k)\underline{\hat{\mathbf{V}}}^{H}_{\text{ut}}(k)$.

[0090] Because of the reciprocal channel and the calibration, the singular value decomposition only need to be performed by either the user terminal or the access point to obtain both matrices $\underline{\hat{\mathbf{V}}}_{\text{ut}}(k)$ and $\underline{\hat{\mathbf{U}}}_{\text{ap}}(k)$. If performed by the user terminal, then the matrices $\underline{\hat{\mathbf{V}}}_{\text{ut}}(k)$ are used for spatial processing at the user terminal and the matrices $\underline{\hat{\mathbf{U}}}_{\text{ap}}(k)$ may be sent back to the access point.

[0091] The access point may also be able to obtain the matrices $\underline{\hat{\mathbf{U}}}_{\text{ap}}(k)$ and $\underline{\hat{\Sigma}}(k)$ based on a steered reference sent by the user terminal. Similarly, the user terminal may also be able to obtain the matrices $\underline{\hat{\mathbf{V}}}_{\text{ut}}(k)$ and $\underline{\hat{\Sigma}}(k)$ based on a steered reference sent by the access point. The steered reference is described in detail in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309.

[0092] The matrices $\underline{\hat{\mathbf{U}}}_{\text{ap}}(k)$ and $\underline{\hat{\Sigma}}(k)$ may be used to transmit independent data streams on the N_S eigenmodes of the MIMO channel, where $N_S \leq \min\{N_{ap}, N_{ut}\}$. The

spatial processing to transmit multiple data streams on the downlink and uplink is described below.

A. Uplink Spatial Processing

[0093] The spatial processing by the user terminal for an uplink transmission may be expressed as:

$$\underline{\mathbf{x}}_{up}(k) = \underline{\hat{\mathbf{K}}}_{ut}(k)\underline{\hat{\mathbf{V}}}_{ut}(k)\underline{\mathbf{s}}_{up}(k) \quad , \text{for } k \in K , \qquad \text{Eq (24)}$$

where $\underline{\mathbf{x}}_{up}(k)$ the transmit vector for the uplink for the k-th subband; and

$\underline{\mathbf{s}}_{up}(k)$ is a "data" vector with up to N_S non-zero entries for the modulation symbols to be transmitted on the N_S eigenmodes of the k-th subband.

[0094] Additional processing may also be performed on the modulation symbols prior to transmission. For example, channel inversion may be applied across the data subbands (e.g., for each eigenmode) such that the received SNR is approximately equal for all data subbands. The spatial processing may then be expressed as:

$$\underline{\mathbf{x}}_{up}(k) = \underline{\hat{\mathbf{K}}}_{ut}(k)\underline{\hat{\mathbf{V}}}_{ut}(k)\underline{\mathbf{W}}_{up}(k)\underline{\mathbf{s}}_{up}(k) \quad , \text{for } k \in K , \qquad \text{Eq (25)}$$

where $\underline{\mathbf{W}}_{up}(k)$ is a matrix with weights for the (optional) uplink channel inversion.

[0095] The channel inversion may also be performed by assigning transmit power to each subband before the modulation takes place, in which case the vector $\underline{\mathbf{s}}_{up}(k)$ includes the channel inversion coefficients and the matrix $\underline{\mathbf{W}}_{up}(k)$ can be omitted from equation (25). In the following description, the use of the matrix $\underline{\mathbf{W}}_{up}(k)$ in an equation indicates that the channel inversion coefficients are not incorporated into the vector $\underline{\mathbf{s}}_{up}(k)$. The lack of the matrix $\underline{\mathbf{W}}_{up}(k)$ in an equation can indicate either (1) channel inversion is not performed or (2) channel inversion is performed and incorporated into the vector $\underline{\mathbf{s}}_{up}(k)$.

[0096] Channel inversion may be performed as described in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309 and in U.S. Patent Application Serial No. 10/229,209, entitled "Coded MIMO Systems with Selective Channel Inversion Applied Per Eigenmode," filed August 27, 2002, assigned to the assignee of the present application and incorporated herein by reference.

[0097] The received uplink transmission at the access point may be expressed as:

$$\underline{\mathbf{r}}_{up}(k) = \underline{\mathbf{H}}_{up}(k)\underline{\mathbf{x}}_{up}(k) + \underline{\mathbf{n}}(k) \quad , \text{for } k \in K, \qquad \text{Eq (26)}$$

$$\approx \hat{\underline{\mathbf{U}}}_{ap}(k)\hat{\underline{\Sigma}}(k)\underline{\mathbf{s}}_{up}(k) + \underline{\mathbf{n}}(k)$$

where $\underline{\mathbf{r}}_{up}(k)$ is the received vector for the uplink for the k-th subband;

$\underline{\mathbf{n}}(k)$ is additive white Gaussian noise (AWGN) for the k-th subband; and

$\underline{\mathbf{x}}_{up}(k)$ is as shown in equation (24).

[0098] The spatial processing (or matched filtering) at the access point for the received uplink transmission may be expressed as:

$$\hat{\underline{\mathbf{s}}}_{up}(k) = \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{U}}}_{ap}^{H}(k)\underline{\mathbf{r}}_{up}(k)$$

$$= \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{U}}}_{ap}^{H}(k)(\hat{\underline{\mathbf{U}}}_{ap}(k)\hat{\underline{\Sigma}}(k)\underline{\mathbf{s}}_{up}(k) + \underline{\mathbf{n}}(k)) \quad , \text{for } k \in K, \qquad \text{Eq (27)}$$

$$= \underline{\mathbf{s}}_{up}(k) + \tilde{\underline{\mathbf{n}}}(k)$$

where $\hat{\underline{\mathbf{s}}}_{up}(k)$ is an estimate of the vector $\underline{\mathbf{s}}_{up}(k)$ transmitted by the user terminal on the uplink, and $\tilde{\underline{\mathbf{n}}}(k)$ is the post-processed noise. Equation (27) assumes that channel inversion was not performed at the transmitter and that the received vector $\underline{\mathbf{r}}_{up}(k)$ is as shown in equation (26).

B. Downlink Spatial Processing

[0099] The spatial processing by the access point for a downlink transmission may be expressed as:

$$\underline{\mathbf{x}}_{dn}(k) = \hat{\underline{\mathbf{K}}}_{ap}(k)\hat{\underline{\mathbf{U}}}_{ap}^{*}(k)\underline{\mathbf{s}}_{dn}(k) \quad , \text{for } k \in K, \qquad \text{Eq (28)}$$

where $\underline{\mathbf{x}}_{dn}(k)$ is the transmit vector and $\underline{\mathbf{s}}_{dn}(k)$ is the data vector for the downlink.

[00100] Again, additional processing (e.g., channel inversion) may also be performed on the modulation symbols prior to transmission. The spatial processing may then be expressed as:

$$\underline{\mathbf{x}}_{dn}(k) = \hat{\underline{\mathbf{K}}}_{ap}(k)\hat{\underline{\mathbf{U}}}_{ap}^{*}(k)\underline{\mathbf{W}}_{dn}(k)\underline{\mathbf{s}}_{dn}(k) \quad , \text{for } k \in K, \qquad \text{Eq (29)}$$

where $\underline{\mathbf{W}}_{dn}(k)$ is a matrix with weights for the (optional) downlink channel inversion.

[00101] The received downlink transmission at the user terminal may be expressed as:

$$\underline{\mathbf{r}}_{dn}(k) = \underline{\mathbf{H}}_{dn}(k)\underline{\mathbf{x}}_{dn}(k) + \underline{\mathbf{n}}(k) \quad , \text{ for } k \in K , \qquad \text{Eq (30)}$$

$$\approx \hat{\underline{\mathbf{V}}}_{ut}^{*}(k)\hat{\underline{\Sigma}}(k)\underline{\mathbf{s}}_{dn}(k) + \underline{\mathbf{n}}(k)$$

where $\underline{\mathbf{x}}_{dn}(k)$ is the transmit vector as shown in equation (28).

[00102] The spatial processing (or matched filtering) at the user terminal for the received downlink transmission may be expressed as:

$$\begin{aligned}\hat{\underline{\mathbf{s}}}_{dn}(k) &= \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{V}}}_{ut}^{T}(k)\underline{\mathbf{r}}_{dn}(k) \\ &= \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{V}}}_{ut}^{T}(k)(\hat{\underline{\mathbf{V}}}_{ut}^{*}(k)\hat{\underline{\Sigma}}(k)\underline{\mathbf{s}}_{dn}(k) + \underline{\mathbf{n}}(k)) \quad , \text{for } k \in K . \qquad \text{Eq (31)} \\ &= \underline{\mathbf{s}}_{dn}(k) + \tilde{\underline{\mathbf{n}}}(k)\end{aligned}$$

Equation (31) assumes that channel inversion was not performed at the transmitter and that the received vector $\underline{\mathbf{r}}_{dn}(k)$ is as shown in equation (30).

[00103] Table 2 summarizes the spatial processing at the access point and user terminal for data transmission and reception. Table 2 assumes that the additional processing by $\underline{\mathbf{W}}(k)$ is performed at the transmitter. However, if this additional processing is not performed, then $\underline{\mathbf{W}}(k)$ can be regarded as the identify matrix.

Table 2

	Uplink	**Downlink**
User Terminal	Transmit : $\underline{\mathbf{x}}_{up}(k) = \hat{\underline{\mathbf{K}}}_{ut}(k)\hat{\underline{\mathbf{V}}}_{ut}(k)\underline{\mathbf{W}}_{up}(k)\underline{\mathbf{s}}_{up}(k)$	Receive : $\hat{\underline{\mathbf{s}}}_{dn}(k) = \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{V}}}_{ut}^{T}(k)\underline{\mathbf{r}}_{dn}(k)$
Access Point	Receive : $\hat{\underline{\mathbf{s}}}_{up}(k) = \hat{\underline{\Sigma}}^{-1}(k)\hat{\underline{\mathbf{U}}}_{ap}^{H}(k)\underline{\mathbf{r}}_{up}(k)$	Transmit : $\underline{\mathbf{x}}_{dn}(k) = \hat{\underline{\mathbf{K}}}_{ap}(k)\hat{\underline{\mathbf{U}}}_{ap}^{*}(k)\underline{\mathbf{W}}_{dn}(k)\underline{\mathbf{s}}_{dn}(k)$

[00104] In the above description and as shown in Table 2, the correction matrices $\hat{\underline{\mathbf{K}}}_{ap}(k)$ and $\hat{\underline{\mathbf{K}}}_{ut}(k)$ are used for the transmit spatial processing at the access point and user terminal, respectively. This can simplify the overall spatial processing since the modulation symbols may need to be scaled anyway (e.g., for channel inversion) and the correction matrices $\hat{\underline{\mathbf{K}}}_{ap}(k)$ and $\hat{\underline{\mathbf{K}}}_{ut}(k)$ may be combined with the weight matrices $\underline{\mathbf{W}}_{dn}(k)$ and $\underline{\mathbf{W}}_{up}(k)$ to obtain gain matrices $\underline{\mathbf{G}}_{dn}(k)$ and $\underline{\mathbf{G}}_{up}(k)$, where $\underline{\mathbf{G}}_{dn}(k) = \underline{\mathbf{W}}_{dn}(k)\hat{\underline{\mathbf{K}}}_{ap}(k)$ and $\underline{\mathbf{G}}_{up}(k) = \underline{\mathbf{W}}_{up}(k)\hat{\underline{\mathbf{K}}}_{ut}(k)$. The processing may also be

performed such that the correction matrices are used for the receive spatial processing (instead of the transmit spatial processing).

4. MIMO-OFDM System

[00105] **FIG. 5** is a block diagram of an embodiment of an access point 502 and a user terminal 504 within a TDD MIMO-OFDM system. For simplicity, the following description assumes that the access point and user terminal are each equipped with four transmit/receive antennas.

[00106] On the downlink, at access point 502, a transmit (TX) data processor 510 receives traffic data (i.e., information bits) from a data source 508 and signaling and other information from a controller 530. TX data processor 510 formats, codes, interleaves, and modulates (i.e., symbol maps) the data to provide a stream of modulation symbols for each eigenmode used for data transmission. A TX spatial processor 520 receives the modulation symbol streams from TX data processor 510 and performs spatial processing to provide four streams of transmit symbols, one stream for each antenna. TX spatial processor 520 also multiplexes in pilot symbols as appropriate (e.g., for calibration).

[00107] Each modulator (MOD) 522 receives and processes a respective transmit symbol stream to provide a corresponding stream of OFDM symbols. Each OFDM symbol stream is further processed by a transmit chain within modulator 522 to provide a corresponding downlink modulated signal. The four downlink modulated signals from modulator 522a through 522d are then transmitted from four antennas 524a through 524d, respectively.

[00108] At user terminal 504, antennas 552 receive the transmitted downlink modulated signals, and each antenna provides a received signal to a respective demodulator (DEMOD) 554. Each demodulator 554 (which includes a receive chain) performs processing complementary to that performed at modulator 522 and provides received symbols. A receive (RX) spatial processor 560 then performs spatial processing on the received symbols from all demodulators 554 to provide recovered symbols, which are estimates of the modulation symbols sent by the access point. During calibration, RX spatial processor 560 provides a calibrated downlink channel estimate, $\underline{\hat{\mathbf{H}}}_{cdn}(k)$, based on the MIMO pilot transmitted by the access point.

[00109] An RX data processor 570 processes (e.g., symbol demaps, deinterleaves, and decodes) the recovered symbols to provide decoded data. The decoded data may include recovered traffic data, signaling, and so on, which are provided to a data sink 572 for storage and/or a controller 580 for further processing. During calibration, RX data processor 570 provides the calibrated uplink channel estimate, $\underline{\hat{\mathbf{H}}}_{cup}(k)$, which is derived by the access point and sent on the downlink.

[00110] Controllers 530 and 580 control the operation of various processing units at the access point and user terminal, respectively. During calibration, controller 580 may receive the channel response estimates $\underline{\hat{\mathbf{H}}}_{cdn}(k)$ and $\underline{\hat{\mathbf{H}}}_{cup}(k)$, derive the correction matrices $\underline{\hat{\mathbf{K}}}_{ap}(k)$ and $\underline{\hat{\mathbf{K}}}_{ut}(k)$, provide the matrices $\underline{\hat{\mathbf{K}}}_{ut}(k)$ to a TX spatial processor 592 for uplink transmission, and provide the matrices $\underline{\hat{\mathbf{K}}}_{ap}(k)$ to a TX data processor 590 for transmission back to the access point. Memory units 532 and 582 store data and program codes used by controllers 530 and 580, respectively.

[00111] The processing for the uplink may be the same or different from the processing for the downlink. Data and signaling are processed (e.g., coded, interleaved, and modulated) by a TX data processor 590 and further spatially processed by TX spatial processor 592, which multiplexes in pilot symbols during calibration. The pilot and modulation symbols are further processed by modulators 554 to generate uplink modulated signals, which are then transmitted via antennas 552 to the access point.

[00112] At access point 110, the uplink modulated signals are received by antennas 524, demodulated by demodulators 522, and processed by an RX spatial processor 540 and an RX data processor 542 in a complementary to that performed at the user terminal. During calibration, RX spatial processor 560 also provides a calibrated uplink channel estimate, $\underline{\hat{\mathbf{H}}}_{cup}(k)$, based on the MIMO pilot transmitted by the user terminal. The matrices $\underline{\hat{\mathbf{H}}}_{cup}(k)$ are received by controller 530 and then provided to TX data processor 510 for transmission back to the user terminal.

[00113] **FIG. 6** is a block diagram of a TX spatial processor 520a, which may be used for TX spatial processors 520 and 592 in FIG. 5. For simplicity, the following description assumes that all four eigenmodes are selected for use.

[00114] Within processor 520a, a demultiplexer 632 receives four modulation symbol steams (denoted as $s_1(n)$ through $s_4(n)$) to be transmitted on four eigenmodes, demultiplexes each stream into N_D substreams for the N_D data subbands, and provides four modulation symbol substreams for each data subband to a respective TX subband spatial processor 640. Each processor 640 performs the processing shown in equation (24), (25), (28), or (29) for one subband.

[00115] Within each TX subband spatial processor 640, the four modulation symbol substreams (denoted as $s_1(k)$ through $s_4(k)$) are provided to four multipliers 642a through 642d, which also receive the gains $g_1(k)$, $g_2(k)$, $g_3(k)$, and $g_4(k)$ for the four eigenmodes of the associated subband. For the downlink, the four gains for each data subband are the diagonal elements of the corresponding matrix $\underline{\mathbf{G}}_{\text{dn}}(k)$, where $\underline{\mathbf{G}}_{\text{dn}}(k) = \underline{\hat{\mathbf{K}}}_{\text{ap}}(k)$ or $\underline{\mathbf{G}}_{\text{dn}}(k) = \underline{\mathbf{W}}_{\text{dn}}(k)\underline{\hat{\mathbf{K}}}_{\text{ap}}(k)$. For the uplink, the gains are the diagonal elements of the matrix $\underline{\mathbf{G}}_{\text{up}}(k)$, where $\underline{\mathbf{G}}_{\text{up}}(k) = \underline{\hat{\mathbf{K}}}_{\text{ut}}(k)$ or $\underline{\mathbf{G}}_{\text{up}}(k) = \underline{\mathbf{W}}_{\text{up}}(k)\underline{\hat{\mathbf{K}}}_{\text{ut}}(k)$. Each multiplier 642 scales its modulation symbols with its gain $g_m(k)$ to provide scaled modulation symbols. Multipliers 642a through 642d provides four scaled modulation symbol substreams to four beam-formers 650a through 650d, respectively.

[00116] Each beam-former 650 performs beam-forming to transmit one symbol substream on one eigenmode of one subband. Each beam-former 650 receives one scaled symbol substream $s_m(k)$ and performs beam-forming using the eigenvector $\underline{\mathbf{v}}_m(k)$ for the associated eigenmode. Within each beam-former 650, the scaled modulation symbols are provided to four multipliers 652a through 652d, which also receive four elements, $v_{m,1}(k)$, $v_{m,2}(k)$, $v_{m,3}(k)$, and $v_{m,4}(k)$, of the eigenvector $\underline{\mathbf{v}}_m(k)$ for the associated eigenmode. The eigenvector $\underline{\mathbf{v}}_m(k)$ is the m-th column of the matrix $\underline{\hat{\mathbf{U}}}^*_{\text{ap}}(k)$ for the downlink and is the m-th column of the matrix $\underline{\hat{\mathbf{V}}}_{\text{ut}}(k)$ for the uplink. Each multiplier 652 then multiplies the scaled modulation symbols with its eigenvector value $v_{m,j}(k)$ to provide "beam-formed" symbols. Multipliers 652a through 652d provide four beam-formed symbol substreams (which are to be transmitted from four antennas) to summers 660a through 660d, respectively.

[00117] Each summer 660 receives and sums four beam-formed symbols for the four eigenmodes for each symbol period to provide a preconditioned symbol for an associated transmit antenna. Summers 660a through 660d provides four substreams of preconditioned symbols for four transmit antennas to buffers/multiplexers 670a through 670d, respectively.

[00118] Each buffer/multiplexer 670 receives pilot symbols and the preconditioned symbols from TX subband spatial processors 640 for the N_D data subbands. Each buffer/multiplexer 670 then multiplexes pilot symbols, preconditioned symbols, and zeros for the pilot subbands, data subbands, and unused subbands, respectively, to form a sequence of N_F transmit symbols for that symbol period. During calibration, pilot symbols are transmitted on the designated subbands. Multipliers 668a through 668d cover the pilot symbols for the four antennas with Walsh sequences W_1 through W_4, respectively, assigned to the four antennas, as described above and shown in Table 1. Each buffer/multiplexer 670 provides a stream of transmit symbols $x_i(n)$ for one transmit antenna, where the transmit symbol stream comprises concatenated sequences of N_F transmit symbols.

[00119] The spatial processing and OFDM modulation is described in further detail in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309.

[00120] In various embodiments of the invention as described herein, peer-peer communication between the various user terminals (UTs or STAs) in the same basic service set (BSS) or different BSSs can be implemented as described below. The UTs or STAs that calibrate with a single access point (AP) are members of a basic service set (BSS). The single access point is a common node to all UTs in the BSS. The calibration methods as described above facilitate the following types of communication:

(i) A UT in the BSS can use TX steering to communicate directly with the AP on the uplink (UL) and the AP can use TX steering to communicate with the UTs on the downlink (DL).

(ii) A UT in the BSS can communicate directly with another UT in the same BSS using steering. In this case, this peer-peer communication has to be bootstrapped because neither UT knows the channel between them. In various embodiments, the bootstrap procedure works as follows:

- The initiator of the peer-peer link is the designate AP (DAP), and the other UT is the designated UT (DUT).

- The DAP sends MIMO pilot to the DUT along with a request to establish link, which contains the BSS ID plus the DAP ID. The request needs to be sent in a common mode (i.e. Tx diversity).

- The DUT responds by sending back steered MIMO pilot plus an acknowledgement which contains the DUT ID, its BSS ID, and some rate indicator for the DAP to use.

- The DAP can then use steering on the DL and the DUT can use steering on the UL. Rate control and tracking can be accommodated by breaking the transmissions into DL and UL segments with sufficient time between them to allow for processing.

(iii) UTs that belong to one BSS (e.g., BSS1) can steer to UTs that belong to another BSS (e.g., BSS2), even though each has calibrated with a different AP. However, there will be a phase rotation ambiguity (per subband) in this case. This is because the calibration procedure as described above establishes a reference which is unique to the AP it has calibrated with. The reference is a complex constant,

$$\alpha(k, j) = \frac{g_{APTX}(0)}{g_{APRX}(0)}$$

where k is the subband index and j is the AP index and 0 is the index of the reference antenna (e.g., antenna 0) used on the AP. In one embodiment, this constant is common to all UTs in a given BSS, but is independent for different BSSs.

[00121] As a result, when a UT from BSS1 communicates with a UT in BSS2, steering without correction or compensation for this constant may result in a phase rotation and amplitude scaling of the entire eigensystem. The phase rotation can be determined through the use of pilot (steered and unsteered) and removed in the receivers of each respective UT. In one embodiment, the amplitude correction or compensation can simply be an SNR scaling and can be removed by estimation of the noise floor at each receiver, which may impact rate selection.

[00122] In various embodiments, the peer-peer exchange between UTs that belong to different BSSs may work as follows:

- The initiator of the peer-peer link (e.g., UT in BSS1) is the designate AP (DAP), and the other UT (e.g., UT in BSS2) is the designated UT (DUT).

- The DAP sends MIMO pilot to the DUT along with a request to establish link, which contains the respective BSS ID plus the DAP ID. The request needs to be sent in a common mode (i.e. Tx diversity).

- The DUT responds by sending back steered MIMO pilot plus an acknowledgement which contains DUT ID, its BSS ID, and some rate indicator for the DAP to use.

- The DAP receiver (Rx) can estimate the phase rotation on the uplink (UL) and apply the correction constant to each subband. The DAP can then use steering on the downlink (DL) but needs to include a preamble of steered reference on at least the first steered packet to allow the DUT receiver (Rx) to correct or compensate for the phase rotation on the DL for each subband. Subsequent DL transmissions may not require a steered reference preamble. Rate control and tracking can be accommodated by breaking the transmissions into DL and UL segments with sufficient time between them to allow for processing.

[00123] The calibration techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, the techniques may be implemented at the access point and user terminal within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof.

[00124] For a software implementation, the calibration techniques may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory unit (e.g., memory units 532 and 582 in FIG. 5) and executed by a processor (e.g., controllers 530 and 580, as appropriate). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

[00125] Headings are included herein for reference and to aid in locating certain sections. These headings are not intended to limit the scope of the concepts described

therein under, and these concepts may have applicability in other sections throughout the entire specification.

[00126] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. A method for calibrating downlink and uplink channels in a wireless communication system, comprising:

obtaining an estimate of a downlink channel response;

obtaining an estimate of an uplink channel response;

determining first and second sets of correction factors based on the estimates of the downlink and uplink channel responses; and

calibrating the downlink channel and uplink channel based on the first and second sets of correction factors, respectively, to form a calibrated downlink channel and a calibrated uplink channel.

2. The method of claim 1, wherein the first set of correction factors is used to scale symbols prior to transmission on the downlink channel and the second set of correction factors is used to scale symbols prior to transmission on the uplink channel.

3. The method of claim 1, wherein the first set of correction factors is used to scale symbols received on the downlink channel and the second set of correction factors is used to scale symbols received on the uplink channel.

4. The method of claim 1, wherein the first and second sets of correction factors are determined based on the following equation:

$$\underline{\hat{\mathbf{H}}}_{up}\underline{\hat{\mathbf{K}}}_{ut} = (\underline{\hat{\mathbf{H}}}_{dn}\underline{\hat{\mathbf{K}}}_{ap})^{T} ,$$

where $\underline{\hat{\mathbf{H}}}_{dn}$ is a matrix for the estimate of the downlink channel response,

$\underline{\hat{\mathbf{H}}}_{up}$ is a matrix for the estimate of the uplink channel response,

$\underline{\hat{\mathbf{K}}}_{ap}$ is a matrix for the first set of correction factors,

$\underline{\hat{\mathbf{K}}}_{ut}$ is a matrix for the second set of correction factors, and

"^{T}" denotes a transpose.

5. The method of claim 4, wherein determining the first and second sets of correction factors includes:

computing a matrix $\underline{\mathbf{C}}$ as an element-wise ratio of the matrix $\hat{\underline{\mathbf{H}}}_{up}$ over the matrix $\hat{\underline{\mathbf{H}}}_{dn}$, and

deriving the matrices $\hat{\underline{\mathbf{K}}}_{ap}$ and $\hat{\underline{\mathbf{K}}}_{ut}$ based on the matrix $\underline{\mathbf{C}}$.

6. The method of claim 5, wherein the deriving the matrix $\hat{\underline{\mathbf{K}}}_{ut}$ includes

normalizing each of a plurality of rows of the matrix $\underline{\mathbf{C}}$, and

determining a mean of the plurality of normalized rows of the matrix $\underline{\mathbf{C}}$, and wherein the matrix $\hat{\underline{\mathbf{K}}}_{ut}$ is formed based on the mean of the plurality of normalized rows.

7. The method of claim 5, wherein the deriving the matrix $\hat{\underline{\mathbf{K}}}_{ap}$ includes

normalizing each of a plurality of columns of the matrix $\underline{\mathbf{C}}$, and

determining a mean of inverses of the plurality of normalized columns of the matrix $\underline{\mathbf{C}}$, and wherein the matrix $\hat{\underline{\mathbf{K}}}_{ap}$ is formed based on the mean of the inverses of the plurality of normalized columns.

8. The method of claim 4, wherein the matrices $\hat{\underline{\mathbf{K}}}_{ut}$ and $\hat{\underline{\mathbf{K}}}_{ap}$ are derived based on a minimum mean square error (MMSE) computation.

9. The method of claim 8, wherein the MMSE computation minimizes a mean square error (MSE) given as

$$|\hat{\underline{\mathbf{H}}}_{up}\hat{\underline{\mathbf{K}}}_{ut} - (\hat{\underline{\mathbf{H}}}_{dn}\hat{\underline{\mathbf{K}}}_{ap})^{T}|^{2} .$$

10. The method of claim 1, further comprising:

determining a scaling value indicative of an average difference between the estimate of the downlink channel response and the estimate of the uplink channel response.

11. The method of claim 1, wherein the estimates for the downlink and uplink channel responses are normalized to account for receiver noise floor.

12. The method of claim 1, wherein the determining is performed at a user terminal.

13. The method of claim 4, wherein a first set of matrices of correction factors for the downlink channel is determined for a first set of subbands, the method further comprising:

interpolating the first set of matrices to obtain a second set of matrices of correction factors for the downlink channel for a second set of subbands.

14. The method of claim 1, wherein the estimates of the downlink and uplink channel responses are each obtained based on a pilot transmitted from a plurality of antennas and orthogonalized with a plurality of orthogonal sequences.

15. The method of claim 1 wherein the estimate of the uplink channel response is obtained based on a pilot transmitted on the uplink channel and wherein the estimate of the downlink channel response is obtained based on a pilot transmitted on the downlink channel.

16. The method of claim 1, wherein the TDD system is a multiple-input multiple-output (MIMO) system.

17. The method of claim 1, wherein the TDD system utilizes orthogonal frequency division multiplexing (OFDM).

18. A method for calibrating downlink and uplink channels in a wireless time division duplexed (TDD) multiple-input multiple-output (MIMO) communication system, comprising:

transmitting a pilot on the uplink channel;

obtaining an estimate of an uplink channel response derived based on the pilot transmitted on the uplink channel;

receiving a pilot on the downlink channel;

obtaining an estimate of a downlink channel response derived based on the pilot received on the downlink channel; and

determining first and second sets of correction factors based on the estimates of the downlink and uplink channel responses, wherein a calibrated downlink channel is formed by using the first set of correction factors for the downlink channel and a calibrated uplink channel is formed by using the second set of correction factors for the uplink channel.

19. The method of claim 18, wherein the first and second sets of correction factors are determined based on a minimum mean square error (MMSE) computation.

20. The method of claim 18, wherein the first and second sets of correction factors are determined based on a matrix-ratio computation.

21. The method of claim 18, wherein the first set of correction factors is updated based on calibration with a plurality of user terminals.

22. The method of claim 18, further comprising:

scaling symbols with the first set of correction factors prior to transmission on the downlink.

23. The method of claim 18, further comprising:

scaling symbols with the second set of correction factors prior to transmission on the uplink channel.

24. An apparatus in a wireless time division duplexed (TDD) multiple-input multiple-output (MIMO) communication system, comprising:

means for obtaining an estimate of a response of a downlink channel;

means for obtaining an estimate of a response of an uplink channel; and

means for determining first and second sets of correction factors based on the estimates of the downlink and uplink channel responses, wherein a calibrated downlink channel is formed by using the first set of correction factors for the downlink channel

and a calibrated uplink channel is formed by using the second set of correction factors for the uplink channel.

25. A user terminal in a wireless time division duplexed (TDD) communication system, comprising:

an TX spatial processor operative to transmit a first pilot on an uplink channel;

an RX spatial processor operative to receive a second pilot on a downlink channel and derive an estimate of a downlink channel response based on the received second pilot, and to receive an estimate of an uplink channel response derived based on the transmitted first pilot; and

a controller operative to determine first and second sets of correction factors based on the estimates of the downlink and uplink channel responses, wherein a calibrated downlink channel is formed by using the first set of correction factors for the downlink channel and a calibrated uplink channel is formed by using the second set of correction factors for the uplink channel

26. The user terminal of claim 25, wherein the controller is further operative to determine the first and second sets of correction factor based on a minimum mean square error (MMSE) computation.

27. The user terminal of claim 25, wherein the controller is further operative to determine the first and second sets of correction factor based on a matrix-ratio computation.

28. A method for communication in a wireless system, comprising:

calibrating one or more communication links between a plurality of user stations and one or more access points, based on one or more sets of correction factors derived from estimates of channel responses associated with the one or more communication links, the plurality of user stations including a first user station and a second user station; and

establishing communication between the first and second user stations using steering without performing calibration between the first and second user stations.

29. The method of claim 28 wherein establishing the communication between the first and second user stations comprises:

sending, from the first user station, a pilot and a request to establish a communication link with the second user station;

sending, from the second user station, a steered pilot and an acknowledgment in response to receiving the pilot and the request from first user station;

transmitting information between the first and second user stations using steering based on the steered pilot.

30. The method of claim 29 wherein the request to establish the communication comprises an identifier of a basic service set to which the first user station belongs and an identifier of the first user station.

31. The method of claim 29 wherein the acknowledgment comprises an identifier of the second user station, an identifier of a basic service set to which the second user station belongs, and a data rate indicator.

32. The method of claim 28 wherein the one or more access points includes a first access point associated with a first basic service set (BSS) and a second access point associated with a second BSS, wherein the first user station is calibrated with respect to the first access point and the second user station is calibrated with respect to the second access point, and wherein establishing the communication between the first and second user stations comprises:

sending, from the first user station, a pilot and a request to establish a communication link with the second user station;

sending, from the second user station, a steered pilot and an acknowledgment in response to receiving the pilot and the request from first user station; and

transmitting information between the first and second user stations using steering that is adjusted to compensate for a phase rotation caused by calibration of the first and second user stations with respect to different access points.

33. The method of claim 32 wherein the phase rotation is determined based on the steered pilot received from the second user station.

34. An apparatus for communication in a wireless system, comprising:

means for alibrating one or more communication links between a plurality of user stations and one or more access points, based on one or more sets of correction factors derived from estimates of channel responses associated with the one or more communication links, the plurality of user stations including a first user station and a second user station; and

means for establishing communication between the first and second user stations using steering without performing calibration between the first and second user stations.

35. The apparatus of claim 34 wherein establishing the communication between the first and second user stations comprises:

means for sending, from the first user station, a pilot and a request to establish a communication link with the second user station;

means for sending, from the second user station, a steered pilot and an acknowledgment in response to receiving the pilot and the request from first user station;

means for transmitting information between the first and second user stations using steering based on the steered pilot.

36. The apparatus of claim 35 wherein the request to establish the communication comprises an identifier of a basic service set to which the first user station belongs and an identifier of the first user station.

37. The apparatus of claim 35 wherein the acknowledgment comprises an identifier of the second user station, an identifier of a basic service set to which the second user station belongs, and a data rate indicator.

38. The apparatus of claim 34 wherein the one or more access points includes a first access point associated with a first basic service set (BSS) and a second access point associated with a second BSS, wherein the first user station is calibrated with respect to the first access point and the second user station is calibrated with

respect to the second access point, and wherein establishing the communication between the first and second user stations comprises:

sending, from the first user station, a pilot and a request to establish a communication link with the second user station;

sending, from the second user station, a steered pilot and an acknowledgment in response to receiving the pilot and the request from first user station; and

transmitting information between the first and second user stations using steering that is adjusted to compensate for a phase rotation caused by calibration of the first and second user stations with respect to different access points.

39. The apparatus of claim 38 wherein the phase rotation is determined based on the steered pilot received from the second user station.

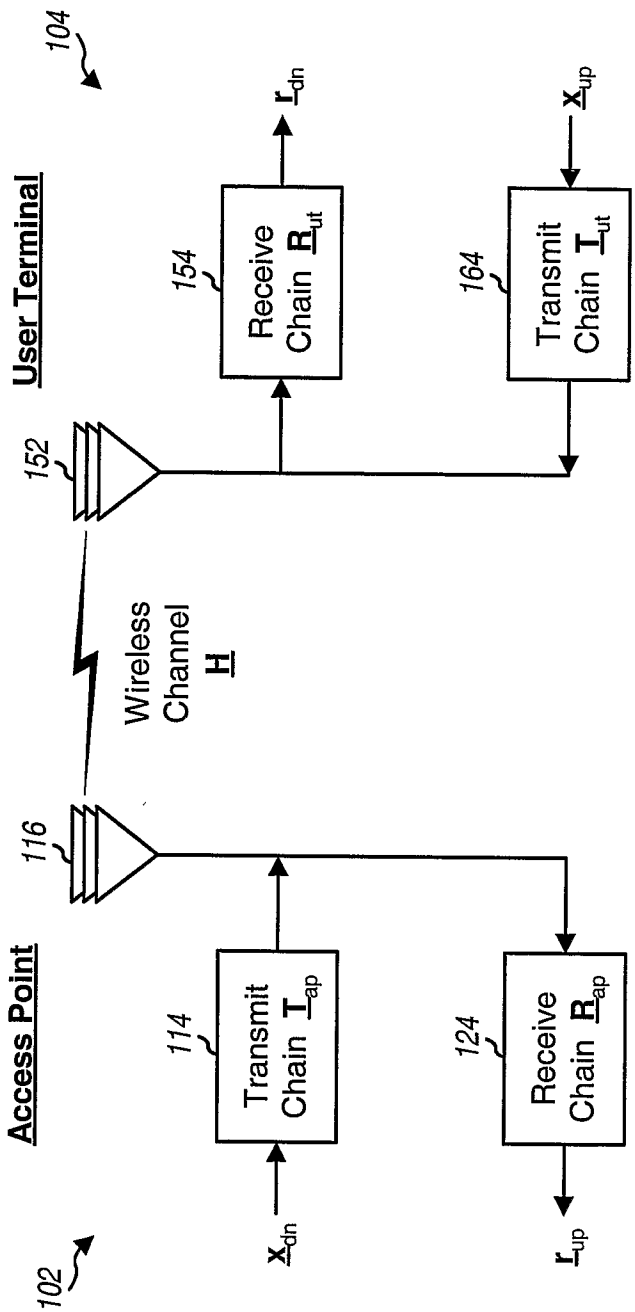
104
User Terminal
152
154
Receive Chain $\underline{R}_{ut}$
164
Transmit Chain $\underline{T}_{ut}$
$\underline{r}_{dn}$
$\underline{x}_{up}$
Wireless Channel $\underline{H}$
Access Point
116
114
Transmit Chain $\underline{T}_{ap}$
124
Receive Chain $\underline{R}_{ap}$
102
$\underline{x}_{dn}$
$\underline{r}_{up}$

FIG. 1

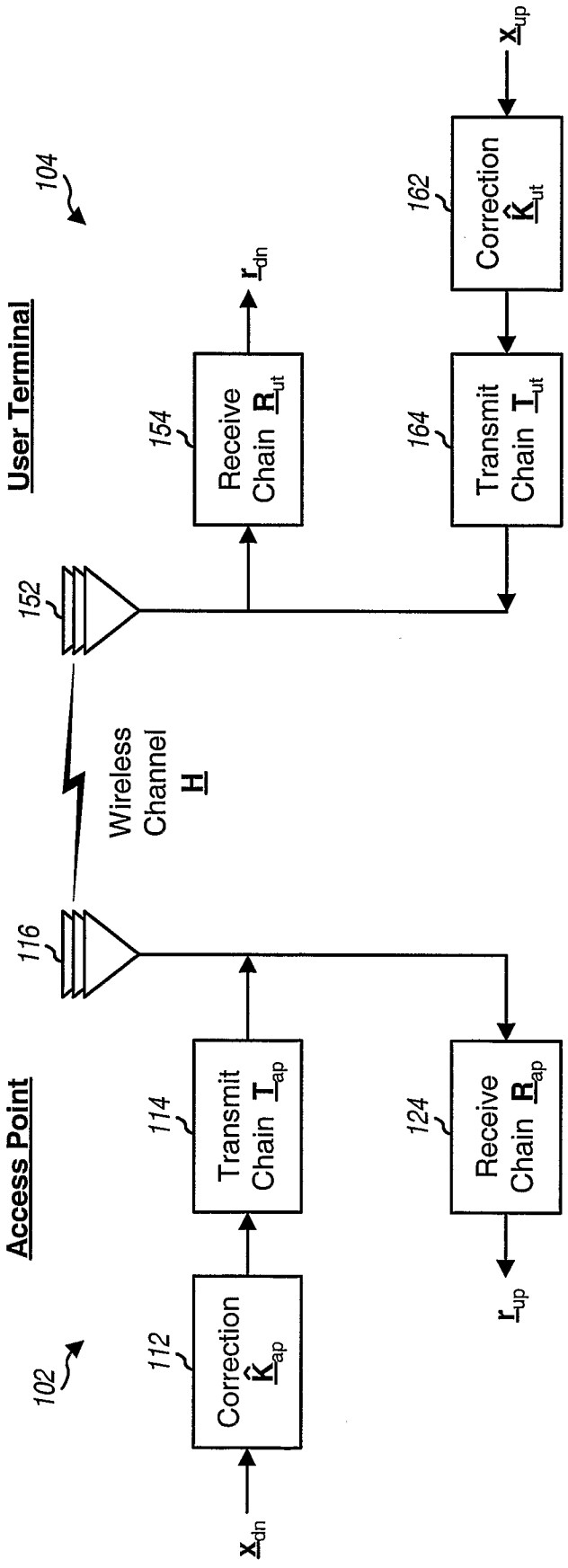
Access Point
User Terminal
102
104
112
Correction
$\hat{\underline{K}}_{ap}$
114
Transmit
Chain $\underline{T}_{ap}$
116
Wireless
Channel
$\underline{H}$
124
Receive
Chain $\underline{R}_{ap}$
152
154
Receive
Chain $\underline{R}_{ut}$
162
Correction
$\hat{\underline{K}}_{ut}$
164
Transmit
Chain $\underline{T}_{ut}$
$\underline{x}_{dn}$
$\underline{r}_{up}$
$\underline{r}_{dn}$
$\underline{x}_{up}$

FIG. 2

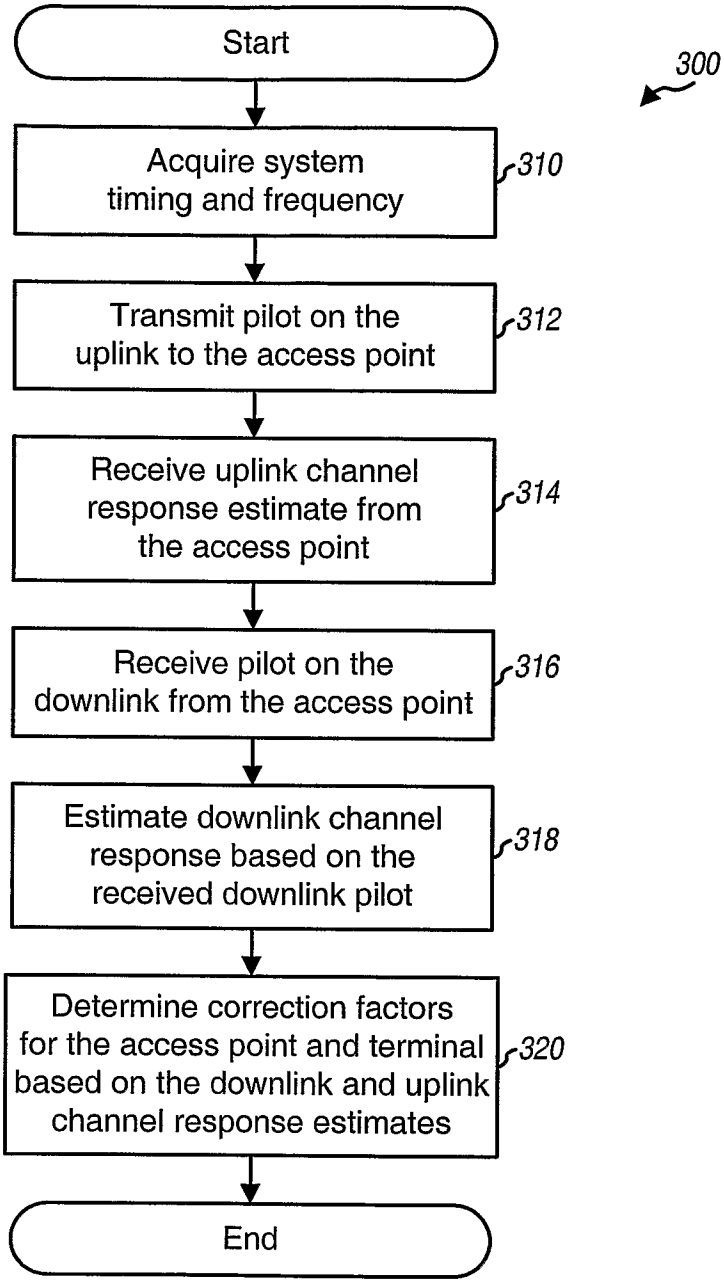
Start
300
Acquire system timing and frequency
310
Transmit pilot on the uplink to the access point
312
Receive uplink channel response estimate from the access point
314
Receive pilot on the downlink from the access point
316
Estimate downlink channel response based on the received downlink pilot
318
Determine correction factors for the access point and terminal based on the downlink and uplink channel response estimates
320
End

FIG. 3

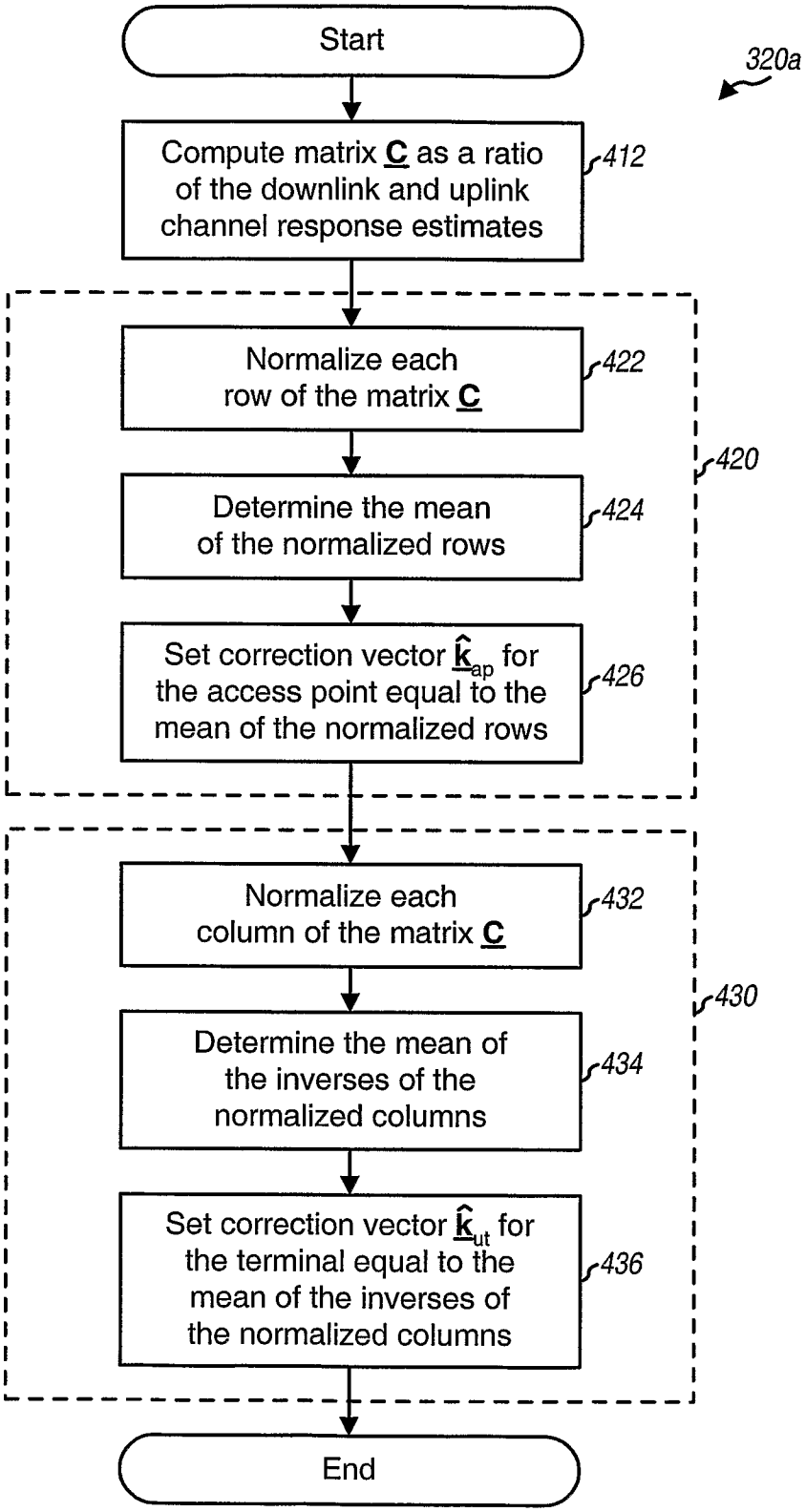
Start
320a
Compute matrix C as a ratio of the downlink and uplink channel response estimates
412
Normalize each row of the matrix C
422
Determine the mean of the normalized rows
424
Set correction vector $\hat{k}_{ap}$ for the access point equal to the mean of the normalized rows
426
420
Normalize each column of the matrix C
432
Determine the mean of the inverses of the normalized columns
434
Set correction vector $\hat{k}_{ut}$ for the terminal equal to the mean of the inverses of the normalized columns
436
430
End

FIG. 4

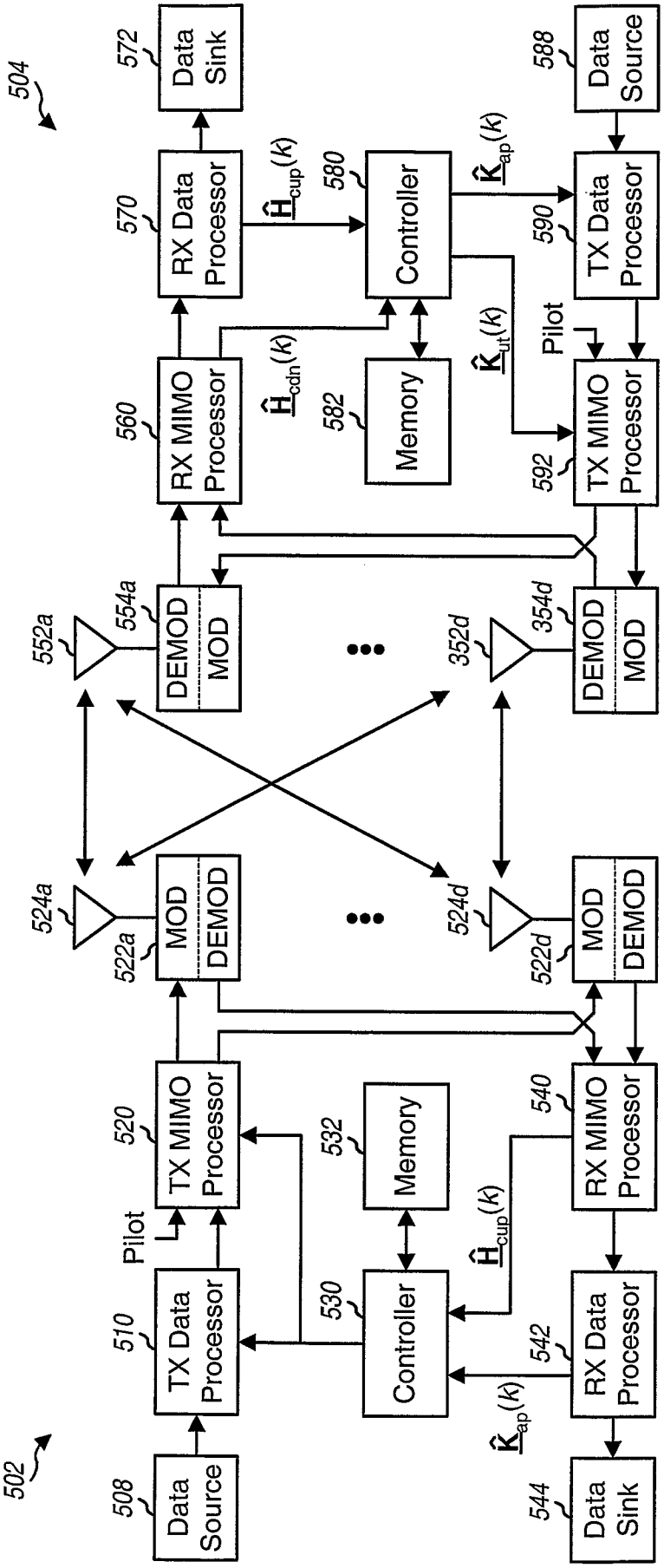
502
504
508
Data Source
510
TX Data Processor
520
TX MIMO Processor
522a
MOD
DEMOD
524a
552a
554a
DEMOD
MOD
560
RX MIMO Processor
570
RX Data Processor
572
Data Sink
580
Controller
582
Memory
588
Data Source
590
TX Data Processor
592
TX MIMO Processor
352d
354d
DEMOD
MOD
524d
522d
MOD
DEMOD
540
RX MIMO Processor
542
RX Data Processor
544
Data Sink
530
Controller
532
Memory
Pilot
Pilot
$\hat{\underline{H}}_{cup}(k)$
$\hat{\underline{H}}_{cdn}(k)$
$\hat{\underline{K}}_{ap}(k)$
$\hat{\underline{K}}_{ut}(k)$
$\hat{\underline{K}}_{ap}(k)$
$\hat{\underline{H}}_{cup}(k)$

FIG. 5

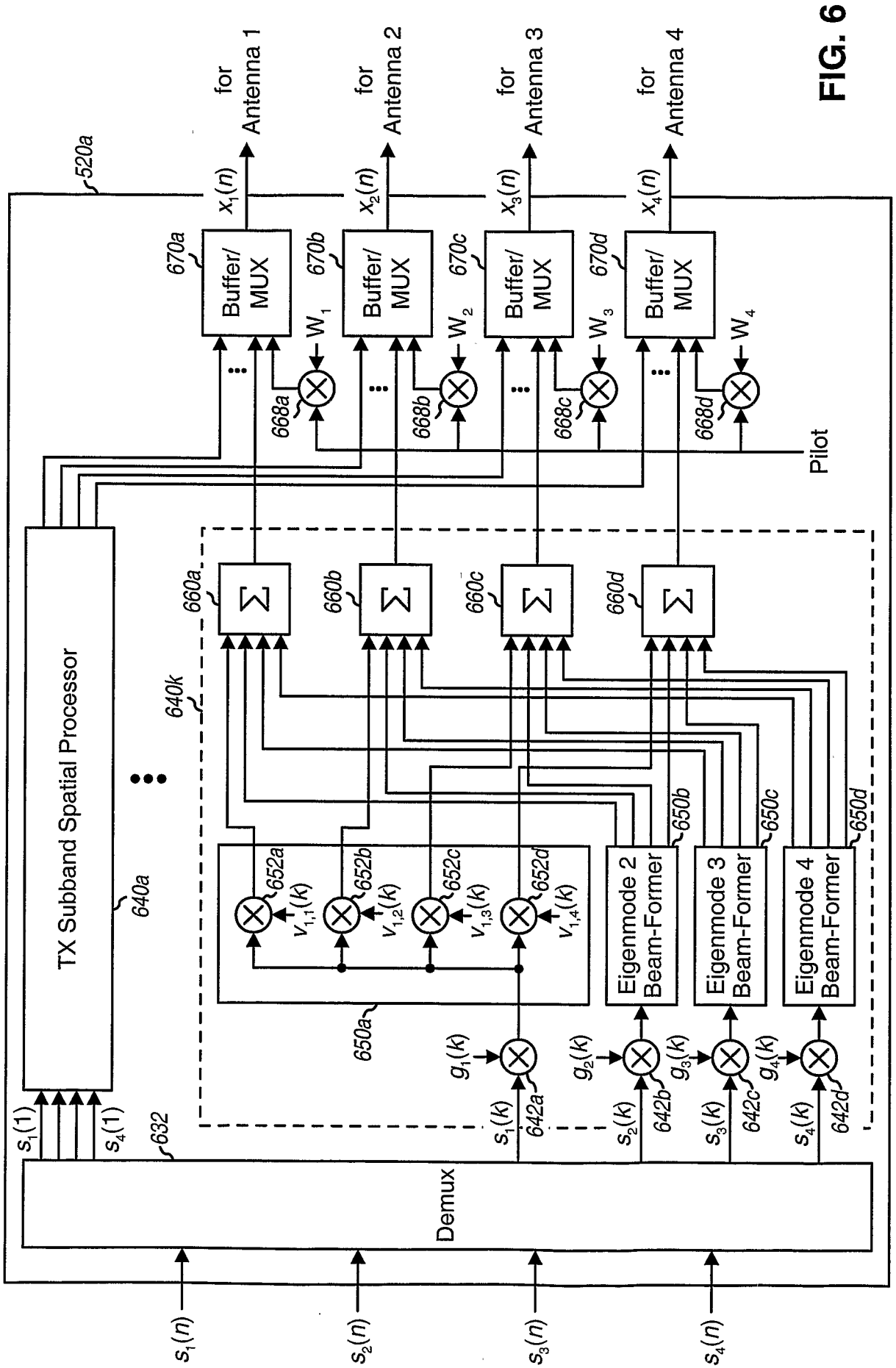
520a
for Antenna 1
for Antenna 2
for Antenna 3
for Antenna 4
$x_1(n)$
$x_2(n)$
$x_3(n)$
$x_4(n)$
670a
670b
670c
670d
Buffer/ MUX
W_1
W_2
W_3
W_4
668a
668b
668c
668d
Pilot
660a
660b
660c
660d
640k
TX Subband Spatial Processor
640a
652a
652b
652c
652d
$v_{1,1}(k)$
$v_{1,2}(k)$
$v_{1,3}(k)$
$v_{1,4}(k)$
650a
650b
650c
650d
Eigenmode 2 Beam-Former
Eigenmode 3 Beam-Former
Eigenmode 4 Beam-Former
$g_1(k)$
$g_2(k)$
$g_3(k)$
$g_4(k)$
$s_1(k)$
$s_2(k)$
$s_3(k)$
$s_4(k)$
642a
642b
642c
642d
632
Demux
$s_1(1)$
$s_4(1)$
$s_1(n)$
$s_2(n)$
$s_3(n)$
$s_4(n)$

FIG. 6